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THE UNIVERSITY OF ALBERTA

Rock Avalanches on Mount Cayley, British Columbia

by

Zhongyou Lu

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF Master of Science

Geology

EDMONTON, ALBERTA

FALL, 1988

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Supervisor

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Date Aug. 3, 1988

ABSTRACT

This thesis studies two major natural events which occurred on Mount Cayley in 1963 and 1984.

It is found that the 1963 event was a rock slide, and the deposits of the 1963 rock avalanche have distinct depositional units which can be traced back to the bedrock in the source area. The accumulation zone of the 1963 rock slide is naturally divided into three separate blocks by their different depositional units and different topographic characteristics.

The 1984 event contained two stages, rock avalanche and debris flow. In the first stage, a rock mass approximately 200x300x150 m detached from the slope, travelled 1.6 km and came to rest around the confluence of Avalanche and Turbid Creeks. In the second stage, debris flow surges were formed by the burst of the debris dam. In the middle stream of Turbid Creek, the debris flow shifted its direction quite often, and even overtopped the top of the escarpment consisting of the 1963 rock avalanche deposits and rushed into Dusty Creek. The velocity of the rock avalanche was 32 m/s, and the velocity of the debris flow was 28-32 m/s determined from superelevations. As the debris flow moved at such a high velocity, a series of special phenomena were created. The most significant ones are high superelevation, uprooted trees, high mud spatters, and wood pieces and rock blocks hurled through air. The debris flow removed the logging road bridge and road approaches completely near the mouth of Turbid Creek, almost blocked the Squamish River during each surge, swept 3 km of logging road and introduced huge quantities of sediments to the channel of the Squamish River. As testing shows that the uniaxial compressive strength of wet tuff specimens is 3.2-4.0 MPa, about 2/3 of the strength of dry specimens, the friction angle of wet tuff specimens is 30°, and the slake durability index of tuff is very low, 26%, tuff layers are not only important in the forming of rock avalanches but also important in the forming of debris flows on Mount Cayley.

To prevent and predict rock avalanches and debris flows, further research should be considered.

Ackowlegement

The author wishes to express his gratitude to his supervisor Dr. D. M. Cruden for his interest and intense enthusiasm in the subject, and his guidance and support for this research. His ideas, time and valuable discussions throughout the course of this research in making it a success are very much appreciated.

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1. INTRODUCTION

1.1 Objectives

This thesis studies two major natural events which occurred on Mount Cayley, British Columbia, Canada in 1963 and 1984. The objectives of this research are to determine:

(1) what slope movements occurred, their localities and dimensions, and what kind of materials were involved;

(2) the major characteristics of these two events;

(3) how the rock mass detached from the slope, what was the path of transportation of rock debris and how these debris deposited;

(4) special phenomena created by these events and their meanings;

(5) Why the deposits of these events have different features; and

(6) the velocities of the rock avalanches and the debris flow.

In addition, the geotechanical properties of volcanic tuff were examined, the relationship between them and slope movement are discussed. The impacts of these events on the environment, logging and recreation in this area need to be assessed. And suggestions of further research to prevent or predict those disasters should be made.

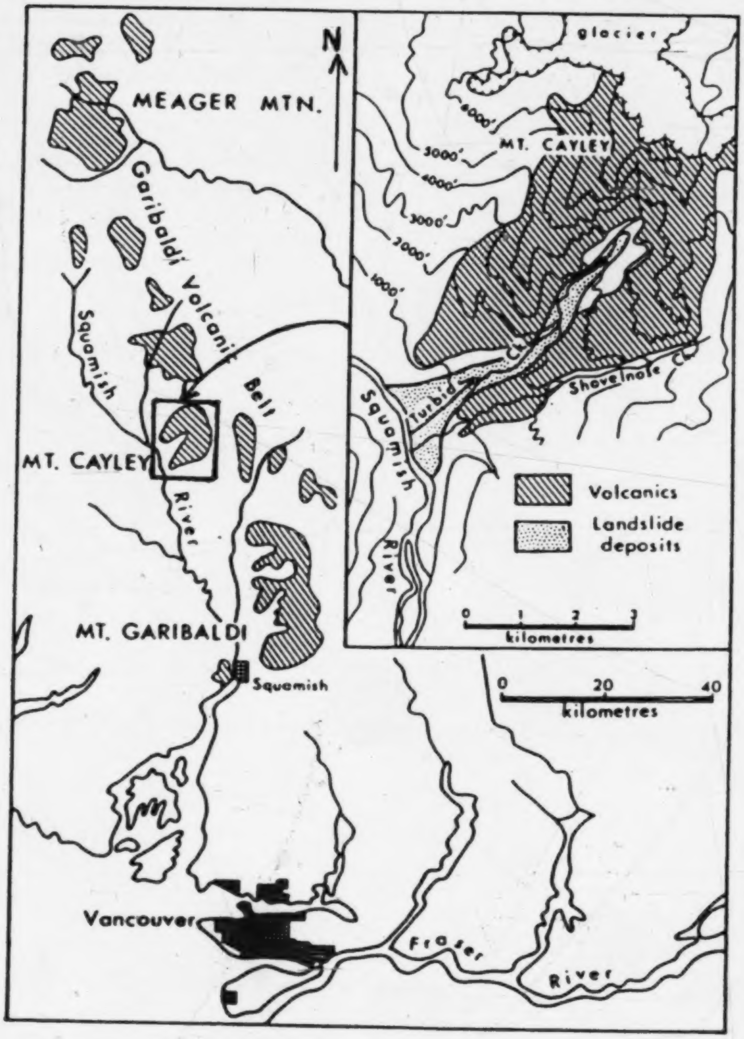
For these purposes, I carried out two months field investigation in July-August 1986 and a laboratory testing programme May-November 1987. Finally, I spent six months on data analysis and thesis preparation.

In this thesis, Chapter 1 describes the objectives, location and accessibility of the study area, research history and geological setting. Chapters 2 and 3 document the 1963 rock avalanche and the 1984 rock avalanche and debris flow respectively. Chapter 4 briefly lists the laboratory testing results. Chapter 5 discusses the relationship between the geotechnical properties of volcanic tuff and slope movements. Finally, Chapter 6 gives the main conclusions and suggestions.

1.2 Location and Accessibility of the Study Area

Mount Cayley is one of the major Quaternary volcanic complexes in British Columbia. It is 90 km north-west of Vancouver (Fig. 1.1) and 40 km north-west of the town of Squamish. Prehistoric rock avalanche and debris flow deposits are common around the margins of Mount Cayley (Clague and Souther 1982). Attention was focused on the two large, young rock avalanches in the valleys of Dusty and Avalanche Creeks, two small tributaries of Turbid Creek. Turbid Creek is one of the major creeks draining Mount Cayley and a tributary of the Squamish River. The study area is narrowed in the valley of Turbid Creek (Fig. 1.2).

Vancouver and Squamish are linked by Highway 99. A logging road starts from Squamish passes the mouth of Tuebid Creek.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Squamish
MT. CAYLEY
River
MT. GARIBALDI
Squamish
Vancouver
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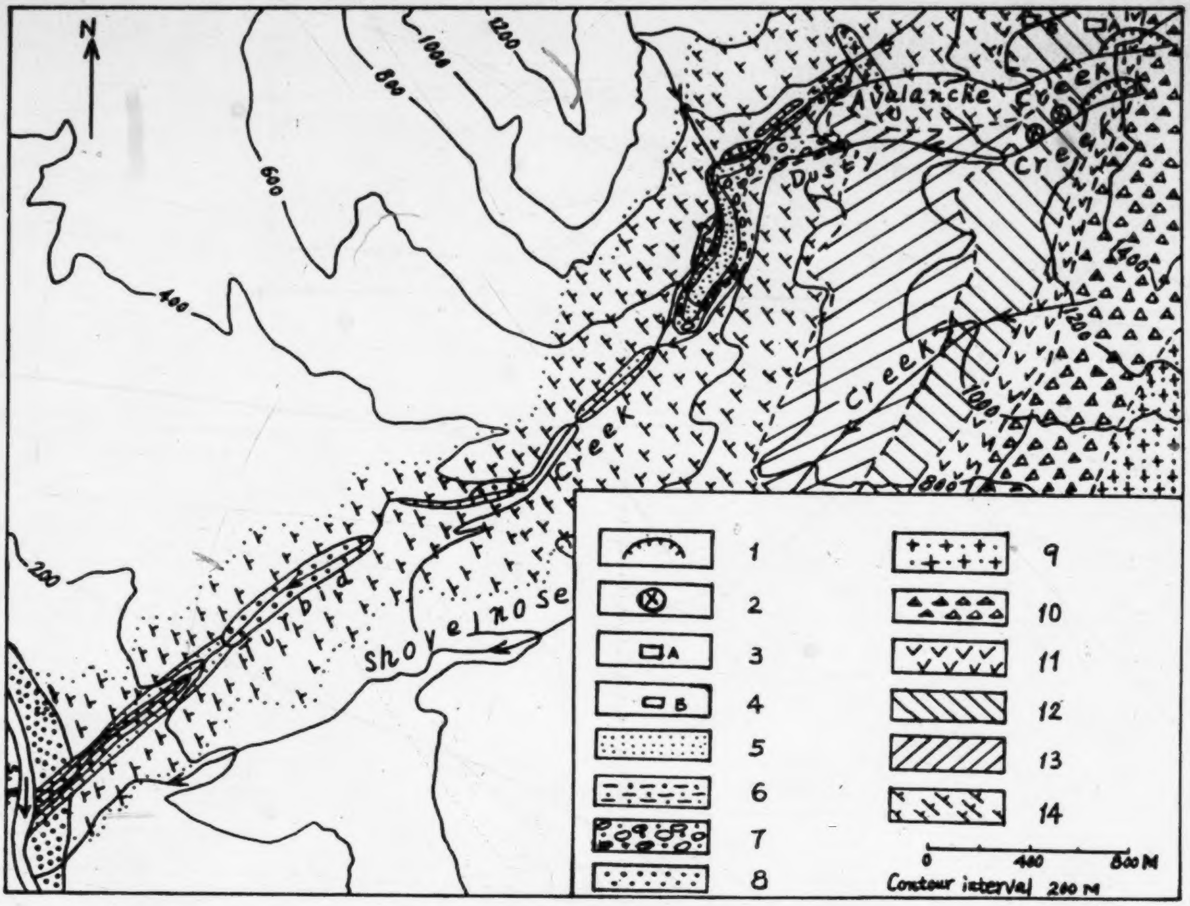
kilometres
glacier
6000'
5000'
4000'
3000'
2000'
1000'
MT. CAYLEY
Turbid
Shovelnose Cr.
Squamish River
Volcanics
Landslide deposits
0 1 2 3
kilometres

Figure 1.1 Location Map (After Clague and Souther, 1982)


N
1200
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800
600
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Avalanche Creek
Dusty
Creek
Creek
Turbid
Creek
Shovelnose
1
2
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A
4
B
5
6
7
8
9
10
11
12
13
14
0
400
800 M
Contour interval 200 M

Figure 1.2 Geologic Map of Study Area

1-Main scarp; 2-Joint measurement site; 3-Location of Fig. 5.1 a, 4-Location of Fig. 5.1 b, Surficial Deposits: 5-1984 debris flow deposits, 6-1984 rock avalanche deposits, 7-1963 rock avalanche deposits, 8-Old rock avalanche deposits, Bedrock: 9-Unit 6 porphyritic dacite, 10-Unit 5 purple lapilli and white tuff, 11-Unit 4 dark brown dacite and grey tuff, 12-Unit 3 grey tuff breccia and dacite, 13-Unit 2 columnar-jointed dacite and tuff, 14-Unit 1 basement rock, granodiorite, quartz diorite and gneiss.

It is quite difficult to get into the upper and middle streams of Turbid Creek. A part of an abandoned logging road was accessible to trucks and vans. In addition, a small trail leads into the middle part of Turbid Creek, the major depositional area, and the lower part of the upstream of Turbid Creek. No access to the head of Turbid Creek was found. It was very difficult to find a safe spot for helicopter landing in the upstream of Turbid Creek.

1.3 Research History

Because of its remote location in the southern Coast Mountains and the difficult access, Mount Cayley and slope movements on it have not been examined in detail until recently. However geological mapping was carried out in 1979 as a part of a geothermal enegy assessment program (Souther 1980). Souther (1980) also reported landslide deposits that both predate and postdate the present forest. The landslide deposits in the Turbid Creek valley on the west side of Mount Cayley, emphasizing the 1963 event, were investigated in detail in 1980 by Clague and Souther (1982). After 1963, rock avalanches and debris flows have occurred resulting in damage to the logging road bridge at the mouth of Turbid Creek 5 times and the wash out of a logging road. Among those debris flows, the 1984 event is the largest and most significant one. This event highlights the need for caution in the development of Mount Cayley.

1.4 Geologic Setting

Mount Cayley is one of about 12 Quaternary volcanoes forming the Mount Garibaldi Volcanic Belt, which extends about 120 km from Mount Garibaldi at the head of Howe Sound to Meager Mountain near the head of Lillooet River (Clague and Souther 1982). The age of volcanic activity in this belt ranges from Pliocene to Holocene, the most recent major eruption having occurred at Meager Mountain about 2400 years ago (Nasmith et al. 1967; Read 1979). According to Green et al. (1988), the ages of the volcanic rocks on Mount Cayley are approximately determined as 0.31 to 3.8 Ma.

The present edifice of the Mount Cayley volcanic complex rises to a group of three precipitous pyramidal peaks; Mount Cayley with an elevation of almost 2400 m and the slightly lower but equally rugged summits of Wizard Peak and Pyroclastic Peak. The complex rests on a highly irregular basement surface of plutonic and metamorphic rocks belonging to the Mesozoic to early Tertiary Coast Plutonic Complex. The topography prior to eruption was similar to that of the present Coast Mountains. Thus, the basal members of the Mount Cayley pile rest on a variety of materials, ranging from glaciallyscoured basement rocks to buried colluvium up to 25 m thick (Clague and Souther 1982).

The Mount Cayley complex formed during at least three distinct eruptive periods: the Mount Cayley, Vulcan's Thumb, and Shovelnose stages. The earliest, or Mount Cayley, stage produced a composite pile of dacite flows, tuffs, and breccia. During the subsequent Vulcan's Thumb stage of activity, an extensive tephra cone was superimposed on the southwestern flank of the Mount Cayley edifice. Vulcan's Thumb, the largest in a cluster of slender pinnacles, represents a remnant of vent breccia deposited in the upper part of this volcano. The base of the Vulcan's Thumb succession rests on a steep westerly dipping surface that truncates older deposits of the Mount Cayley stage and laps onto the basement surface. A majority of the Vulcan's Thumb rocks are extensively weathered. The third, or Shovelnose, stage of activity produced two domes and related flows of hypersthene, biotite dacite in the valley of Shovelnose Creek (Green et al. 1988).

1.4.1 Bedrock Geology

According to Souther (1980), the bedrock in the study area consists of six units.

Unit 1 consists of basement rock, granodiorite, quartz diorite, and gneiss.

Unit 2 is the rocks of the Mount Cayley stage which are mainly porphyritic hornblende dacite flows and rhyodacite pyroclastics. The basal unit is a complex of overlapping flows, dykes, and pyroclastic deposits, all of which have undergone moderate to intense hydrothermal alteration. In the Dusty Creek valley, this unit consists of up 150 m of columnar-jointed dacite flows, which overlie a basement surface. A layer of pale green, bedded lapilli tuff, 2-3 m thick, is present locally between these flows and the basement surface.

Unit 3 overlies the basal unit of the Mount Cayley stage. This unit is a complex of coarse breccia, flows and domes. In the source areas of Dusty and Avalanche Creeks, this unit comprises up to 250 m of pyroclastic rocks and subordinate discontinuous flows, all of rhyodacitic composition. The pyroclastics range from loosely aggregated tuff breccia containing angular blocks about 1 m across to laminated green and white lapilli tuff. Although the internal structure of this unit is complicated by lateral variations in the thickness of pyroclastic wedges, most beds dip steeply off the mountain towards the southwest. The related flows and intrusions are characterized by very irregular, sinuous to radiating, small columns, which were formed by joints.

Unit 4 consists of porphyritic biotite rhyodacite flows. In Dusty Creek, a single massive rhyodacite flow, which dips and thickens towards the southeast from 50 to 200 m, disconformably overlies the Mount Cayley sequence. The base of this flow is aphyric to vitreous, and its central part is complexly jointed; a blocky breccia caps the flow.

Unit 5 consists of porphyritic dacite tuff breccia and tuff. In the source area of the 1963 rock avalanche, these pyroclastic rocks consist of up to 150 m of steeply southwestdipping tuff breccia containing angular blocks up to about 3 m across.

Unit 6 is the rocks of the youngest, or Shovelnose, stage consisting mainly of porphyritic dacite flows, domes, and cupolas.

1.4.2 Structures

I mapped planar, nearly vertical, southwest trending joints and north-northwest trending joints. Shear joints parallel to slope, dipping towards the valley, induced by the gravitational stresses in the slope are common in this area. Joints were measured at two spots (Fig. 1.2) and presented in Fig. 1.3. These measurements are insufficient to reach conclusions of the joint pattern in this area, but these data do reveal the major sets of joints.

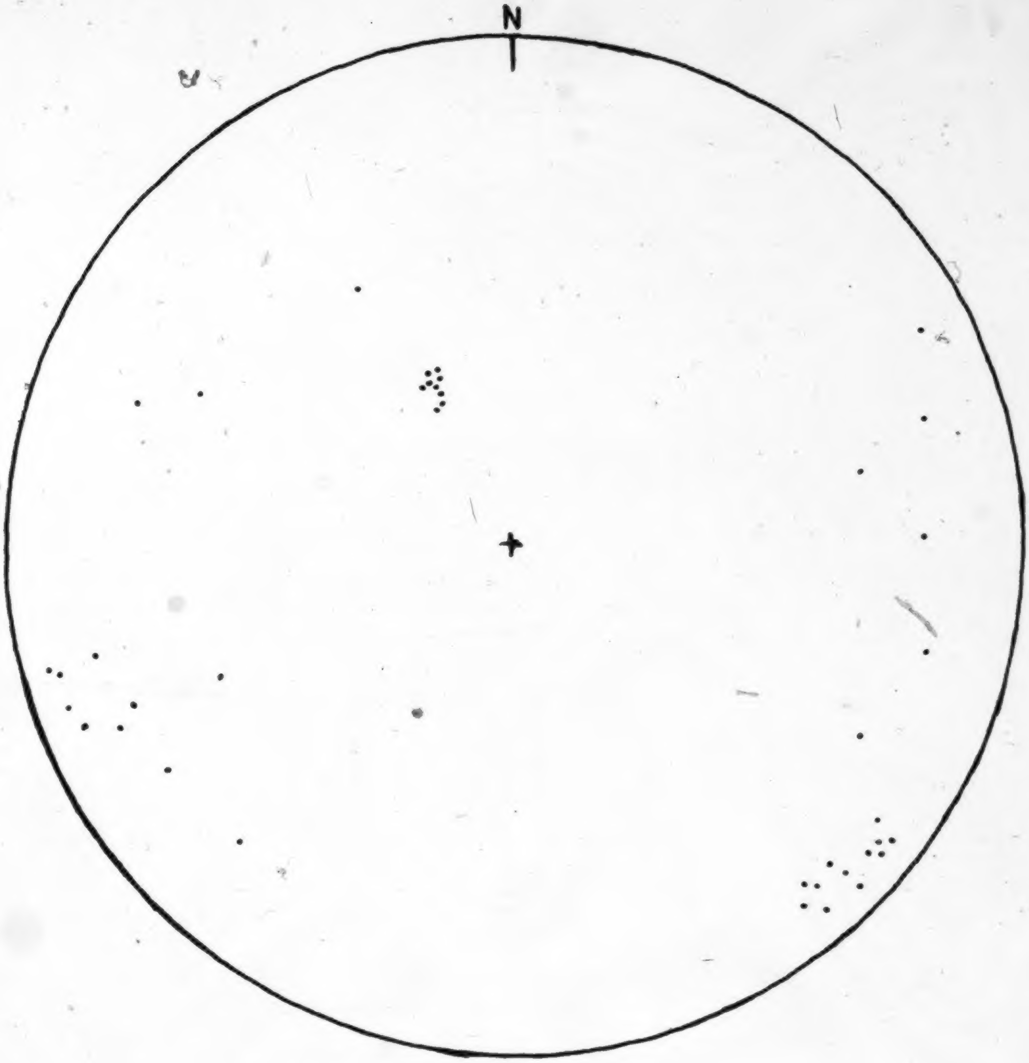

Figure 1.3 Plot of Poles of Joints

2. THE 1963 ROCK AVALANCHE

2.1 Introduction

The 1963 rock avalanche was investigated in detail in 1980 by Clague and Souther (1982) to assess the risk of future slides from Mount Cayley and the impact they might have on possible geothermal installations, roads, and other structures in the adjacent Squamish River valley. As the rock avalanche begins in the valley of Dusty Creek, a small tributary of Turbid Creek, Clague and Souther named it the Dusty Creek landslide.

The main conclusions of Clague and Souther (1982) were:

The 1963 rock avalanche initiated on a west-facing slope at the head of Dusty Creek. Its size was about $5x10^6$ m^3. It probably occurred in July, 1963. The average velocity of debris movement was about 16 m/s. The maximum thickness of moving debris was about 70 m. In most accumulation areas, the deposits could not be subdivided into distinct depositional units except one location-the upper end of the area, where three units of slide debris were recognized.

2.2 Source Area

The source area of the 1963 rock avalanche is a huge bowl (500x250x110 m) on the north side slope of Dusty Creek, next to the source of the creek (Fig. 2.1). As the scarp area is inaccessible, the rock sequences and the weak zones could just be observed at a distance from the opposite side of the scarp in the creek.

2.2.1 Rock Sequences

The rock exposed in the source area can be briefly described as following (from bottom to top) (Fig. 2.2 shows a schematic composite section).

Unit 1 Basement rock, granodiorite, quartz diorite.
Unit 2, Brown columnar-jointed dacite, 80 m. At the bottom there may be pale green, bedded lapilli tuff, 2-3 m.
Unit 3, Brown columnar-jointed dacite at the top and grey-white lapilli tuff and tuff breccia at the bottom, 80 m.
Unit 4, Dark brown columnar-jointed dacite 50-100 m at top and grey tuff 40 m at the bottom.
Unit 5, Purple tuff lapilli 30-50 m and white tuff 20 m.

It is interesting to note that even though the displaced rock mass was broken, these sequences can still be traced in the deposits.

2.2.2 Weak Zones

The main weak zones were

1. The boundary between the volcanic rock and the basement rock, a pre-eruption ground surface dipping south-west at about 22°.
2. Joints.
3. Weak tuff layers.

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Figure 2.1 Source Area of the 1963 Rock Avalanche

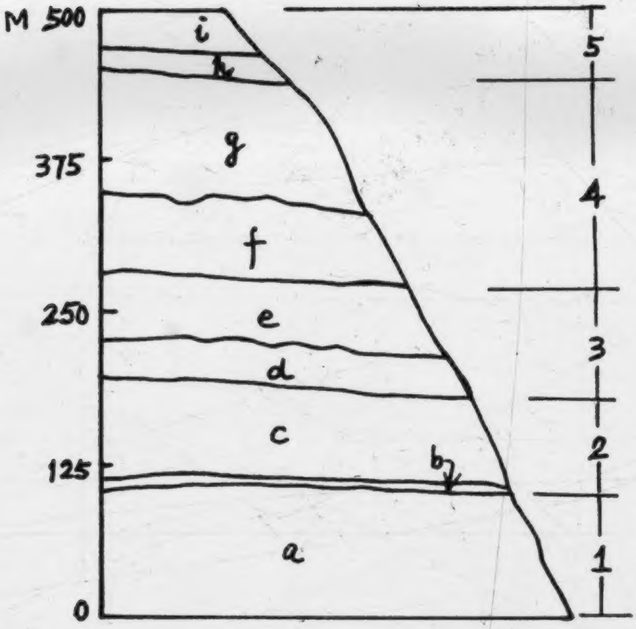

M 500
375
250
125
0
i
h
g
f
e
d
c
b
a
5
4
3
2
1

Figure 2.2 Rock Sequences in Source Area

1,2,3,4, and 5,-Units 1,2,3,4, and 5; a-Basement rock; b-Bedded lapilli tuff; c-Columnar-jointed dacite; d-Lapilli tuff and tuff dreccia; e-Brown columnar-jointed dacite; f-Grey tuff; g-Dark brown columnar-jointed dacite; h-White tuff; i-Purple tuff lapilli.

The displaced mass of the 1963 rock avalanche moved along these weak zones. For example,the main scarp developed along a set of planar southwest-trending, nearly vertical joints (Fig. 2.3 and P, Fig. 2.4). The gently curving northwest lateral margin follows several north-northwest trending faults. And the rupture surface developed along a tuff layer (b, Fig. 2.2).

2.3 Accumulation Area

The debris of the 1963 rock avalanche mainly accumulated in an elongate area between the pre-slide (Point 16, Fig. 2.4) and present mouths of Dusty Creek (Fig. 2.4). The debris extends about 1100 m along the valley of Turbid Creek, and has an average width of 170 m and an average thickness of 25 m. The total accumulation volume is about 4.67×10^6 m^3. The accumulation consists of three major blocks which are bounded by obvious gullys. Also these three major blocks are recognized by their different depositional materials and structures (Figs. 2.5 and 2.6).

2.3.1 Three Major Depositional Blocks

Block 1 is located between the present confluence of Dusty and Turbid Creeks and the significant depression between blocks 1 and 3. It looks like an elongate platform (Fig. 2.7) which is 400 m in length by 90 m in width and an average thickness of 15 m. The total volume of block 1 is approximately 0.54×10^6 m^3.

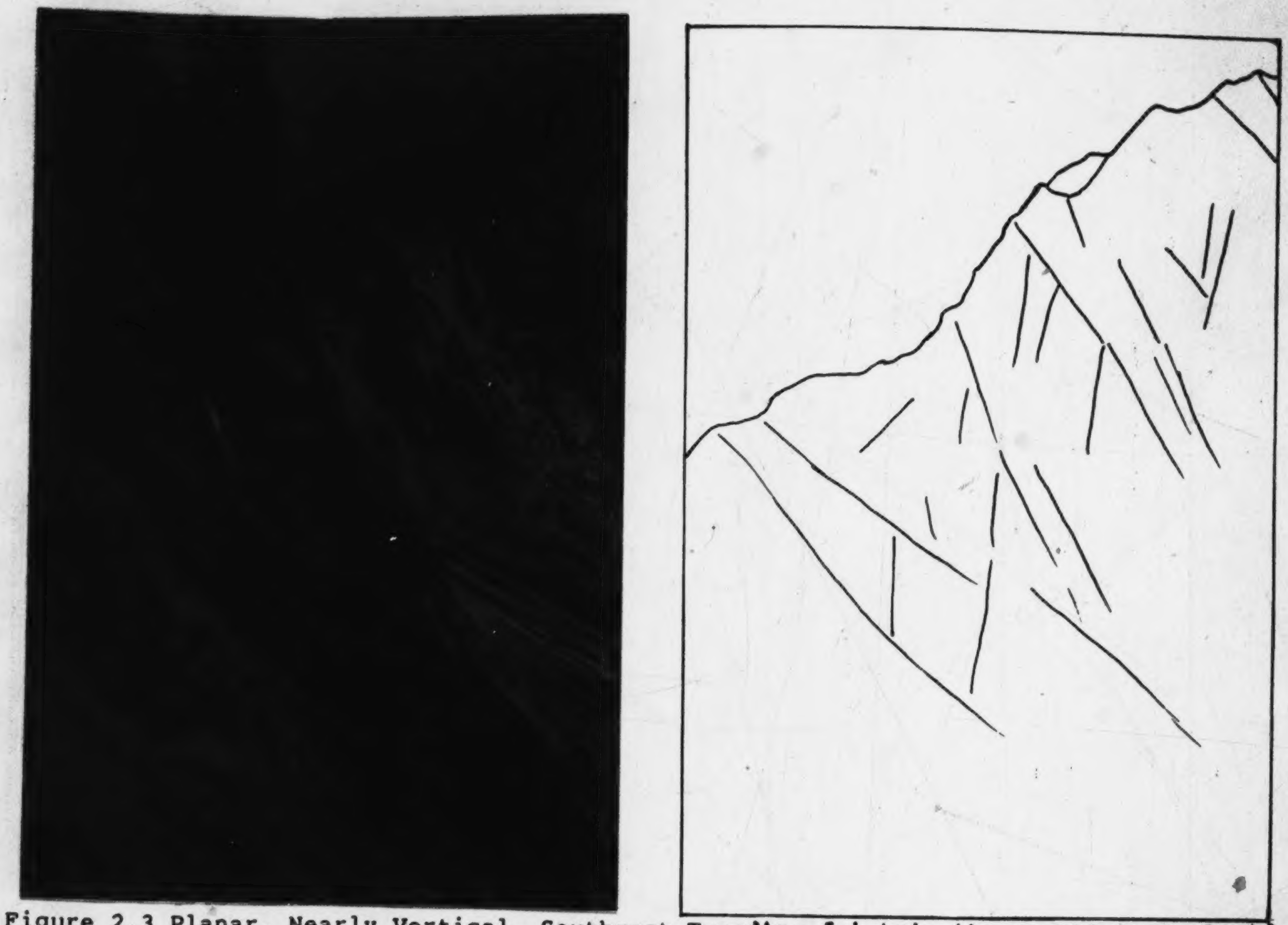


Figure 2.3 Planar, Nearly Vertical, Southwest Trending Jointsin the source area, Looking NW from SE side of Dusty Creek

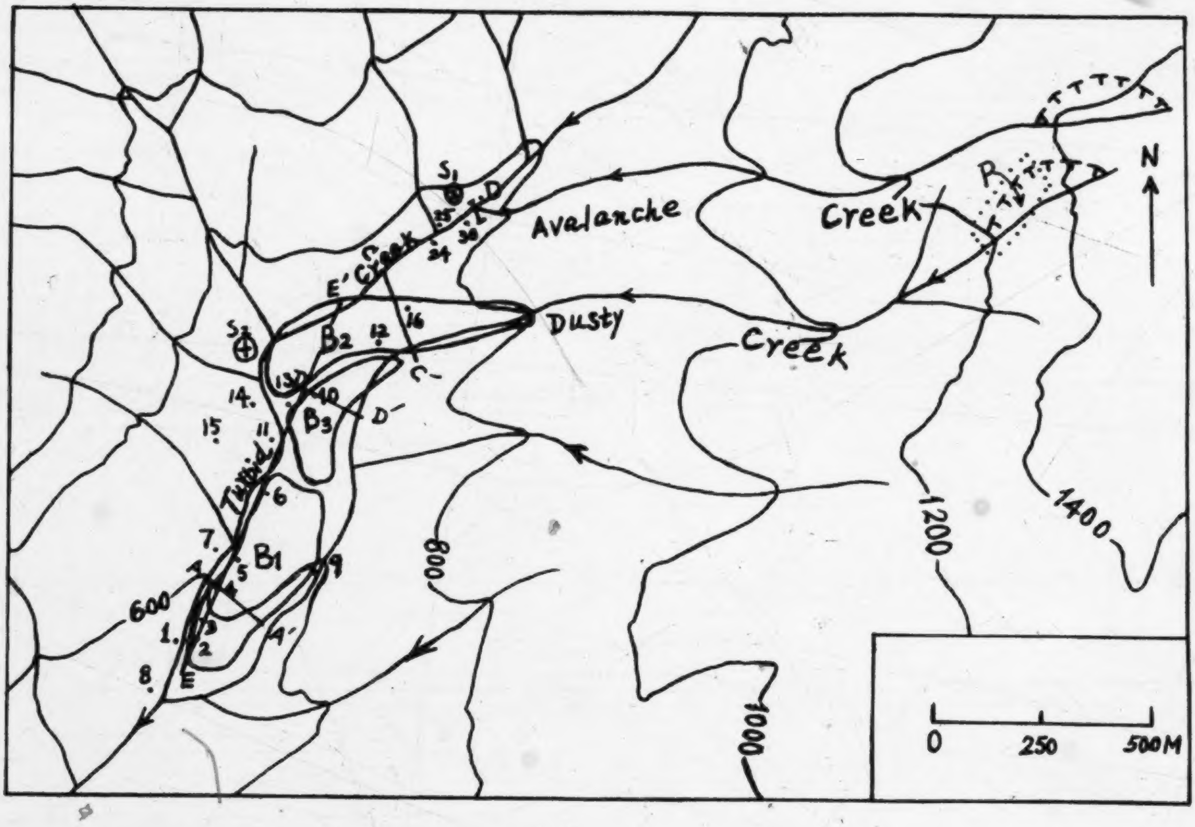

S1
D
25
24
30
Avalanche
Creek
P
N
C
Creek
E'
Dusty
Creek
S2
B2
12
16
C'
13
10
D'
14.
15
11.
B3
Turbid
6
7.
B1
5
4
A
600
9
1.
3
2
A'
8.
E
800
1200
1400
1000
0
250
500M

Figure 2.4 Depositional Area of the 1963 Rock Avalanche B1, B2, and B3-blocks 1, 2 and 3; 1, 2, 6,...-points 1, 2, 6,...; D-Remnant of debris dam; P-Location of Fig. 2.3; S1 and S2-Superelevation sites 1 and 2; A-A', C-C'...-Section lines.

Figure 2.5 Boundary between Blocks 1 and 3, Photo Taken at Point 15 on Fig. 2.4

Figure 2.6 Boundary between Blocks 2 and 3, Photo Taken at Point 11 on Fig. 2.4

The centre of block 2 is located at the pre-slide mouth of Dusty Creek. Block 2 extends to two ends, one of which reaches the right (north-west) bank slope of Turbid Creek, another end heads into Dusty Creek along its right (north) bank slope (Fig. 2.8). Block 2 looks like an arcuate platform. Turbid Creek was blocked by block 2, but has cut through the block already. The profile that Clague and Souther (P. 532 1982) described is at the west end of block 2, on the left bank of No Name Creek, a small tributary of Turbid Creek. The dimensions of block 2 are 390 m in length, 200 m in width and 35 m of an average thickness resulting a total volume of about 2.73x10^6 m^3.

The boundary between blocks 2 and 3 is a gully-like depression. Fig. 2.6 shows that the top surface of block 2 is 5 m higher than that of block 3.

Block 3 is located between blocks 1 and 2, and bounded by the two obvious depressions. Block 3 looks like a dome with a trail elongate downstream. Block 3 (Fig. 2.9) is 310 m in length, 170 m in width and 25 m thick. The volume of block 3 is 1.32x10^6 m^3. The boundary between blocks 3 and1 shown on Fig. 2.5. It looks like a saddle. Obviously, it was formed during the deposition process.

2.3.2 Typical Depositional Profile

Several typical depositional profiles have been recognized and described. These profiles show that most of the 1963 rock avalanche deposits could be subdivided into

Figure 2.7 Block 1, Looking NE from Point 1 on Fig. 2.4

Figure 2.8 Block 2, Looking NE from Point 14 on Fig. 2.4

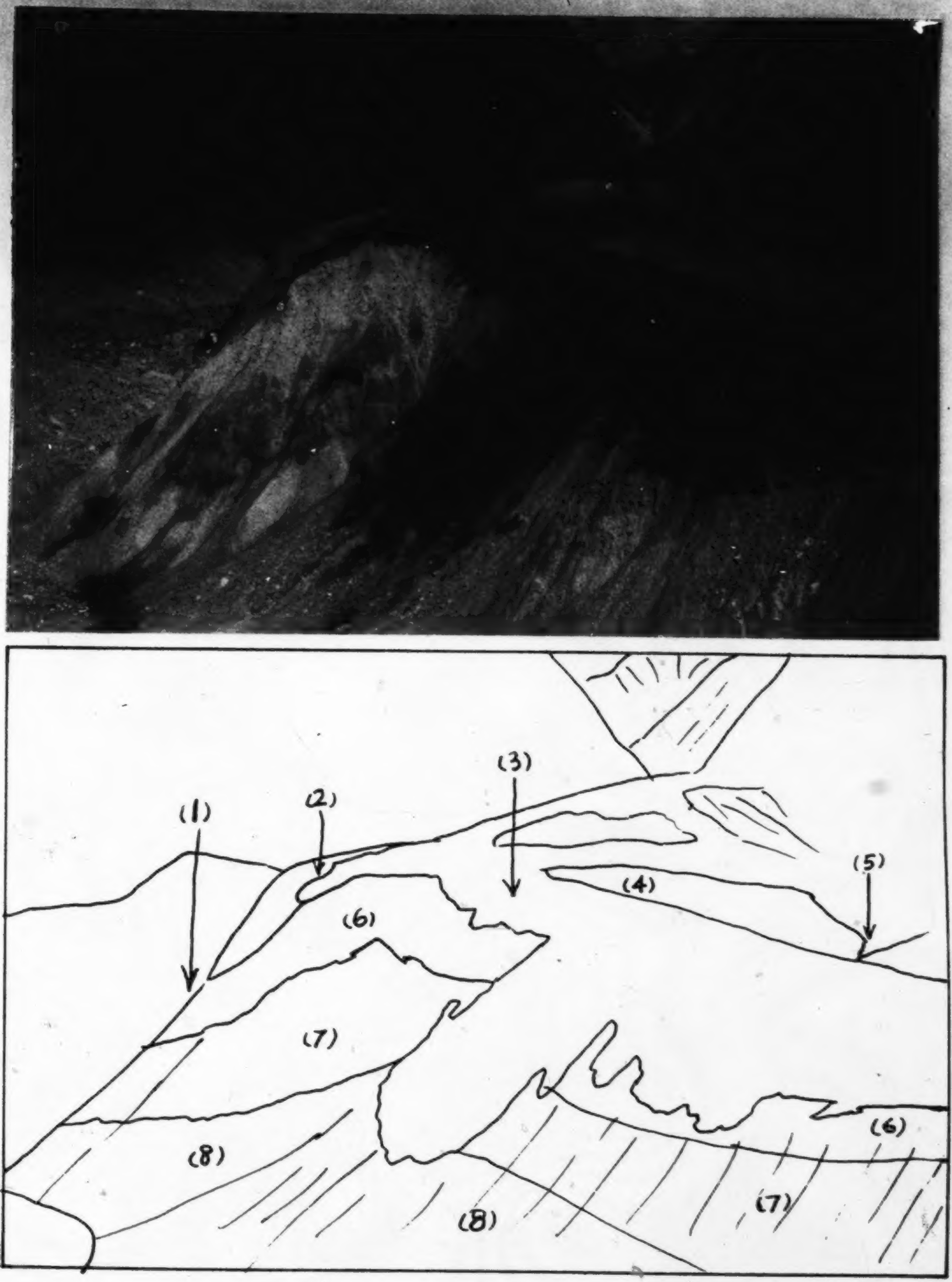


Figure 2.9 Block 3, Looking NEE at Point 15 on Fig. 2.4 (1) Turbid Creek; (2) Block 2; (3) Block 3; (4) Position of Fig. 2.20; (5) Dusty Creek; (6)-(8) 1963 deposits: (6) Purple unit; (7) Dark brown unit; (8) Green-grey unit.

distinct depositional units and the three major blocks have different depositional units. But in every major block, the stratigraphic units could be compared, especially the exposed profiles on the right (northwest) bank slope of Dusty Creek have almost the same stratigraphic structure as that on the left (southeast) bank slope of Turbid Creek. It is also interesting to note that the depositional units in each block are similar to the depositional units of the rocks exposed in the source area.

Three sequences of deposits are described below.

Sequence 1(representing profiles exposed at points 3, 5 and 6)

Descriptions (from base to top):

(1) Basement rock-granodiorite (in place)

(2) Grey or blueish-grey unit: 7 m, 40-50% Of columnar-jointed blocks (general 0.2-0.4 m across, largest block 1 m across), unconformable on basement rock.

(3) Red unit: 5 -8 m, 10-20% of large columnar-jointed dacite boulders (1.5-2.0 m across), 80 % matrix. There is a buried tree layer (0.2 m thick) between the red unit and the following unit. It indicates that the red unit was deposited before the 1963 rock avalanche deposits.

(4) Greenish-grey unit: 6-17 m, mostly small tuff breccia fragments, no boulders.

(5) Brown unit: 3-13 m, mainly columnar-jointed dacite blocks (0.2-1.0 m across) with matrix of greenish tuff breccia.

(6) Grey unit: 2-6 m, mainly small fragments and powder of grey tuff breccia.

(7) 1984 debris flow deposits: 0.5-2.0 m, light yellow tuff breccia and purple lapilli.

As shown in Figures 2.10, 11 and 12, at point 3 (Fig. 2.10) the 1963 rock avalanche deposits directly overlie the basement rock, without older deposits (the red and grey units) in between, at point 5 (Fig. 2.11) the 1963 rock avalanche deposits overlie the red unit, and at point 6, all deposits units can be seen except the basement rock.

In this type of the 1963 rock avalanche deposits, it seems likely that the greenish-grey unit came from Unit 2 of the volcanic rock in the source area; the brown unit and the grey unit cama from Unit 3 of the volcanic rock in the source area. These depositional units are only seen in block 1.

Sequence 2 (representing profiles exposed at points 12 and 16)

Descriptions (from base to top)

(1) Lower grey unit: 6-8 m, grey in colour, 70-80% matrix, mainly small fragments (0.02-0.05 m across), some dacite boulders (0.6-0.8 m across).

(2) Brown unit: 14-18 m, brown in colour, 70% of boulders and blocks consisting mainly of columnar-jointed dacite (0.8-2.0 m across).

(3) Upper grey unit: 5-6 m, mainly small fragments and powder of grey tuff breccia

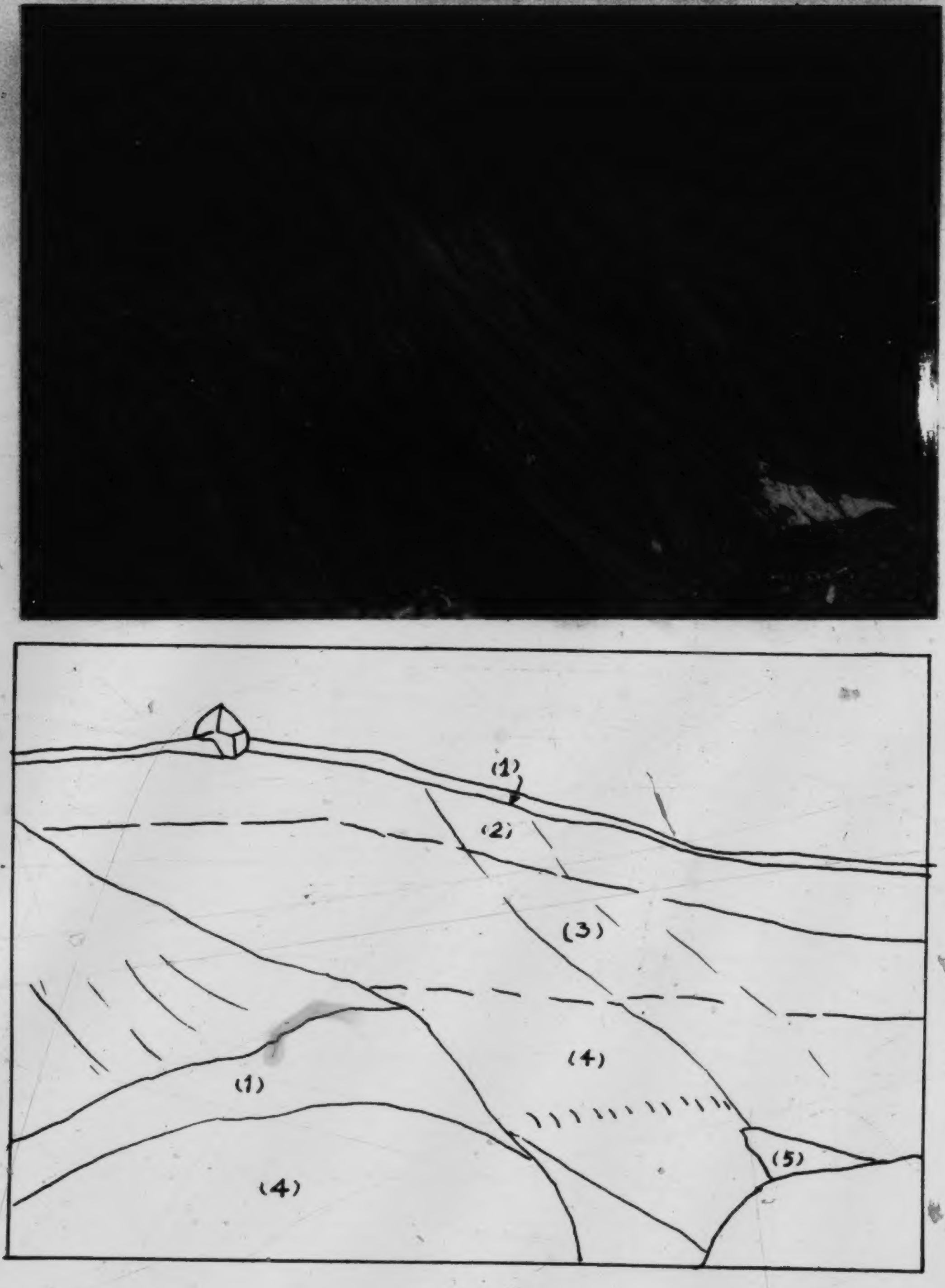


Figure 2.10 The 1963 Deposits Directly Overlie Basement Rock (1) 1984 debris flow deposits; (2)-(4) 1963 rock avalanche deposits: (2) Grey unit; (3) Brown unit; (4) Green-grey unit; (5) Basement rock.

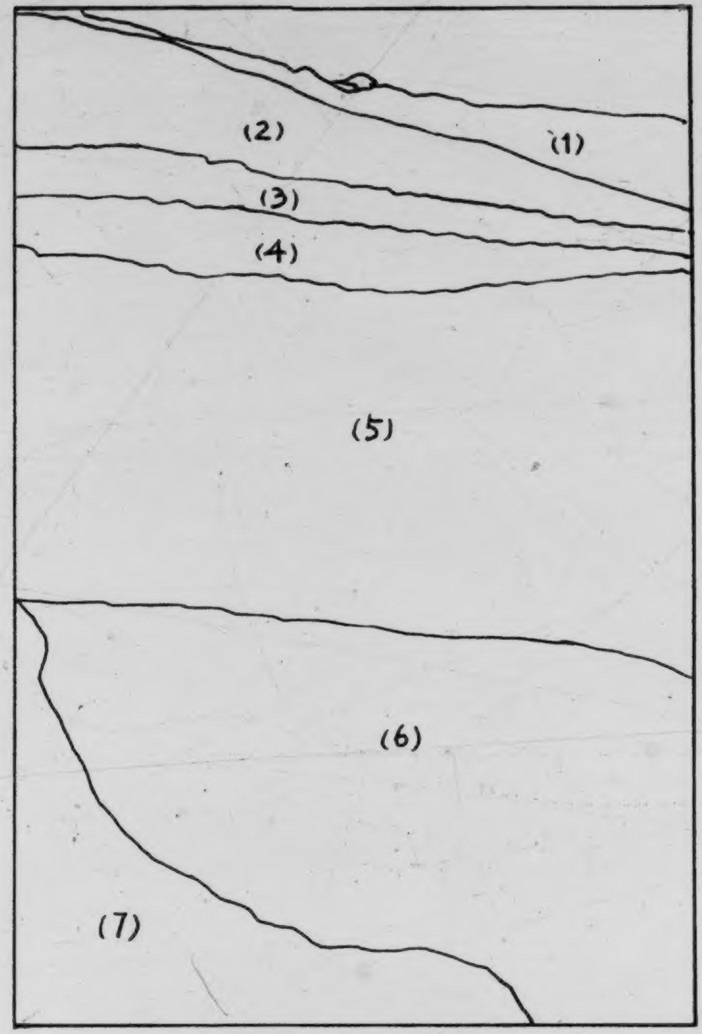


Figure 2.11 The 1963 Deposits Overlie Old Rock Avalanche Deposits, A

(1) 1984 debris flow deposits; (2)-(4) 1963 rock avalanche deposits: (2) Grey unit; (3) Brown unit; (4) Green-grey unit; (5)-(6) Old rock avalanche deposits: (5) Red unit; (6) Blueish-grey unit; (7) Basement rock.

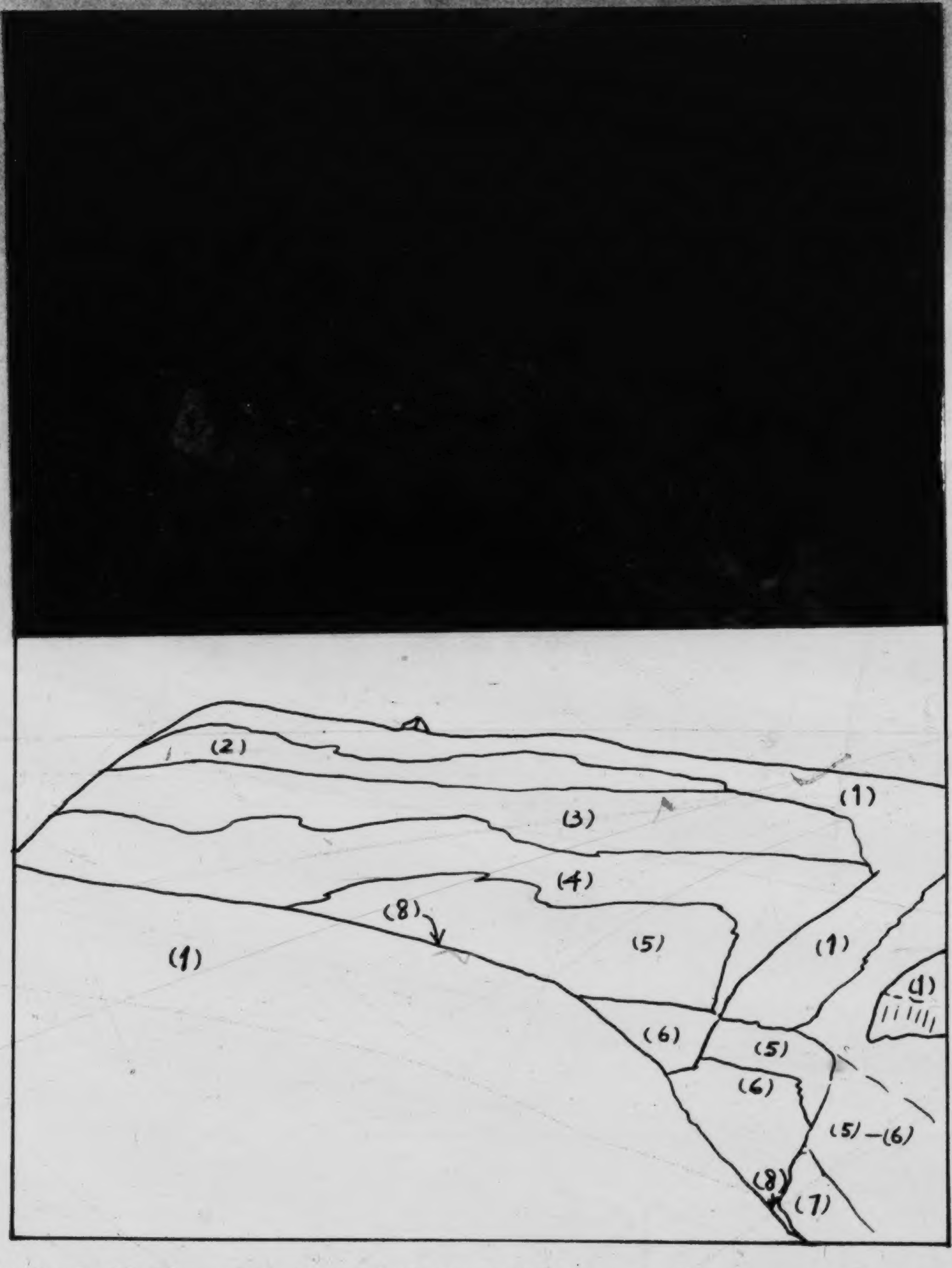


Figure 2.12 The 1963 Deposits Overlie Old Rock Avalanche Deposits, B

(1) 1984 debris flow deposits; (2)-(4) 1963 deposits: (2) Grey unit; (3) Brown unit; (4) Green-grey unit; (5)-(6): Old rock avalanche deposits: (5) Red unit; (6) blueish grey unit; Basement rock; (8) Turbid Creek.

(4) 1984 deposits: 1-5 m, light-yellow and purple blocks and powder of tuff breccia and lapilli.

As shown in Figs. 2.13 and 2.14, this sequence of the 1963 rock avalanche deposits seem to have come from Unit 3 of the volcanic rock in the source area.

Sequence 3 (representing profiles around point 10)

Descriptions (from base to top):

(1) Green-grey unit: 15 m, mainly green-grey in colour, occasionally blue-grey or reddish, mostly small fragments consisting of tuff breccia, few small blocks (0.1- 0.2 m across).

(2) Dark brown unit: 20 m, dominantlyy dark brown, over 50% of blocks and boulders (mainly 0.8-1.0 m across) consisting mainly of dark brown columnar-jointed dacite.

(3)Purple-grey unit: 15 m , mainly small fragments of tuff breccia and purple lapilli, 60-80% of matrix, blocks only seen on the top of the unit (0.2-0.4 m across).

This sequence of the 1963 rock avalanche deposits, as shown in Figures 2.15 and 2.9, seems to have come from Units 4 and 5 of the volcanic rock in the source area (Fig. 2.16).

The following characteristics are recognized:

1. One block has the same type of stratigraphic units at different locations. For example, in block 1, almost a continuous profile of 400 mis exposed on the left (south-east) bank of Turbid Creek, Sequence 1 of the depositional units can be traced throughout the entirely

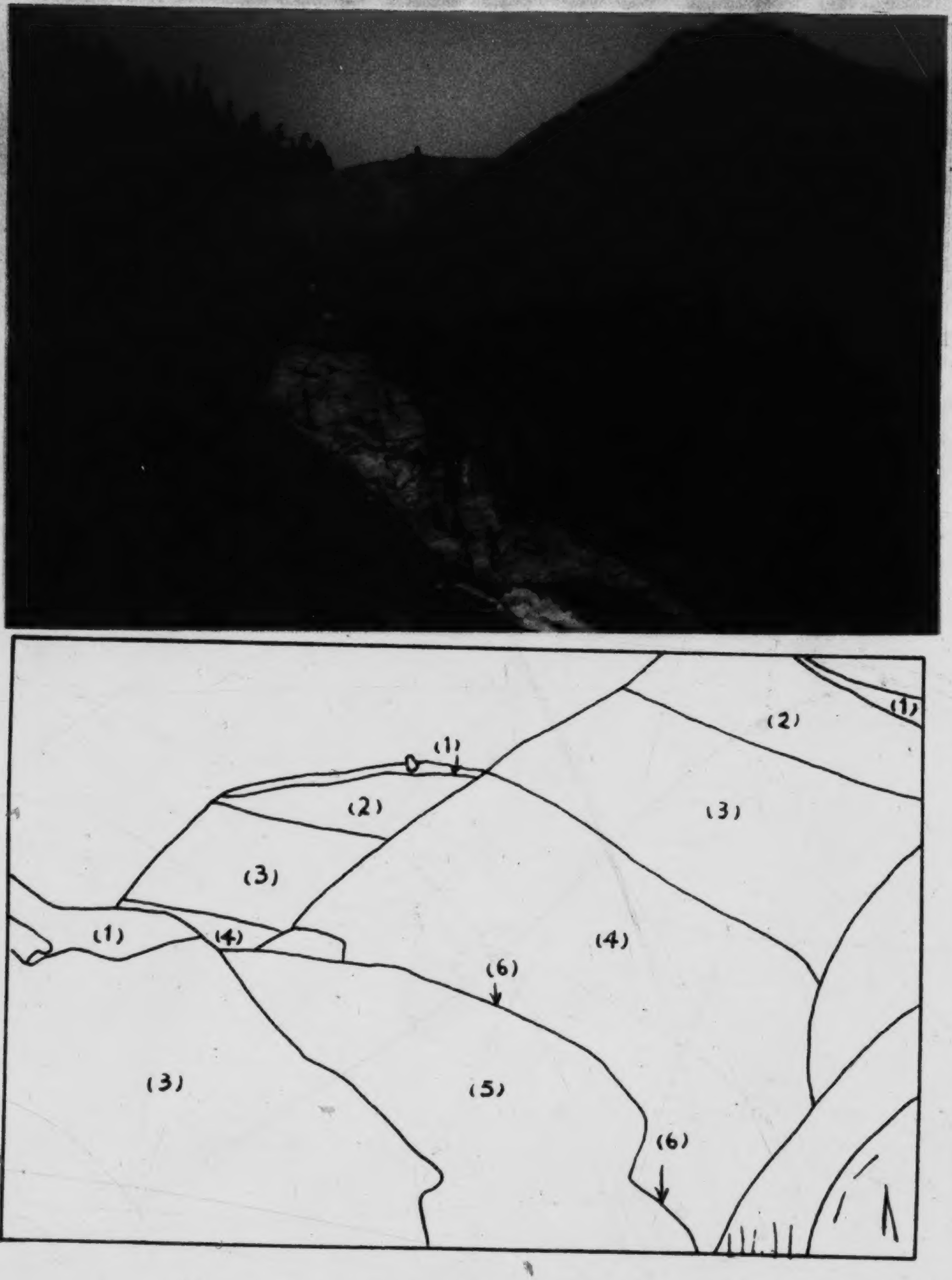


Figure 2.13 1963 Deposits in Block 2, A

(1) 1984 deposits; (2)-(4): 1963 deposits: (2) Upper grey unit; (3) Brown unit; (4) Lower grey unit; (5) Basement rock; (6) Turbid Creek.

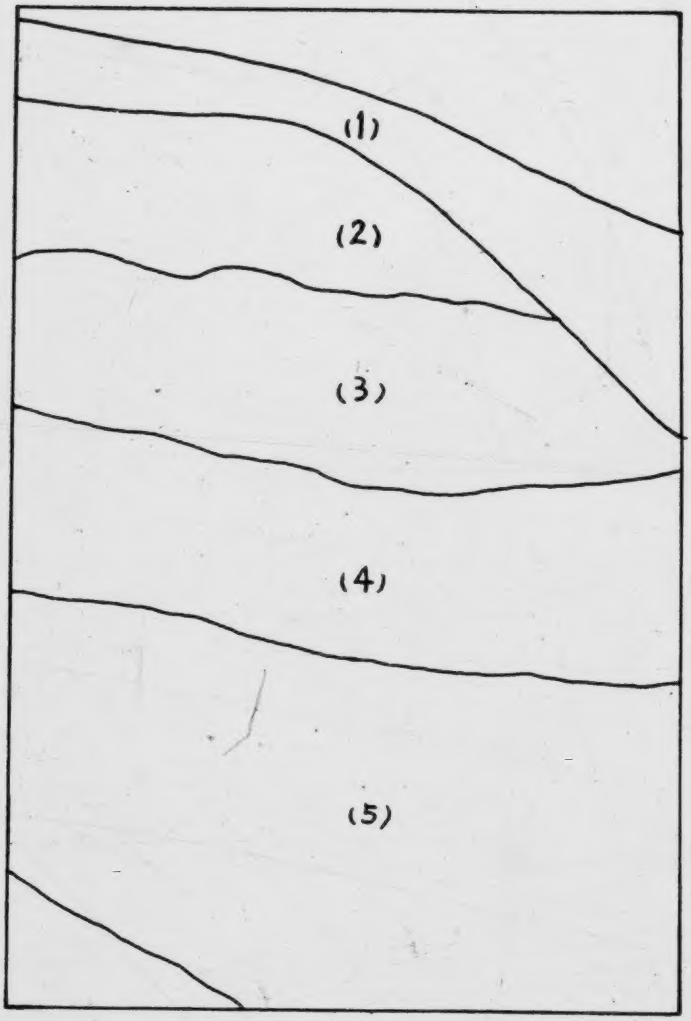


Figure 2.14 1963 Deposits in Block 2, B

(1) 1984 deposits; (2)-(4) 1963 deposits: (2) Upper grey unit; (3) Brown unit; (4) Lower grey unit; (5) Old rock avalanche deposits.

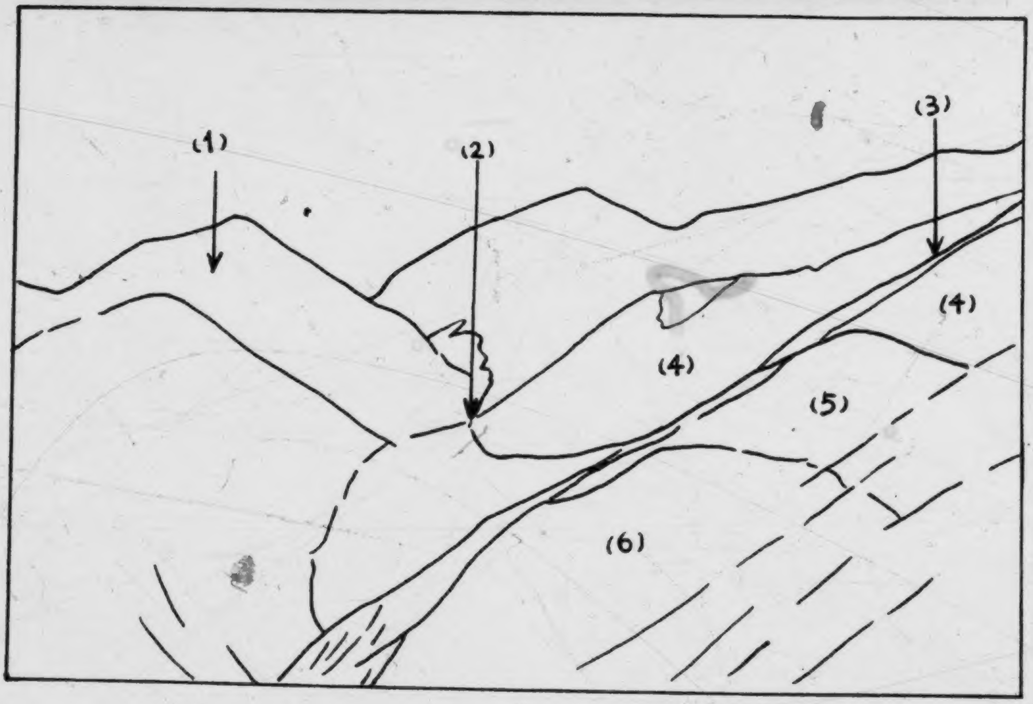


Figure 2.15 1963 Deposits in Block 3

(1) Block 2; (2) Boundary between blocks 2 and 3; (3) Block 3; (4)-(6) 1963 deposits: (4) Purple unit; (5) Dark brown unit; (6) Green-grey unit.

Figure 2.16 Rock Sequences in Source Area, Compare with Fig. 2.9

continuous profile. The same depositional units and structure were observed at the other side of the block, on the right (north-west) bank of Dusty Creek. These phenomena are clearly revealed on Fig. 2.17.

The same characteristics were also observed in blocks 2 and 3 (Figs. 2.18, 19 and 20).

2. For different blocks, the depositional units are different, and could not be compared with each other. This characteristic is revealed by the profile along Turbid Creek (Fig. 2.21).

3. The depositional units in different depositional blocks correspond to different rock units . For example, block 1 corresponds to Units 2 and 3, block 2, Unit 3 and block 3, Units 4 and 5.

Some new understanding about the accumulation area of the 1963 rock avalanche have been reached:

A. The whole accumulation area consists mainly of three major blocks which are shown on Fig. 2.4.

B. The three major blocks are recognized not only by the topographic configurations but also by the different stratigraphic units which make up the different blocks.

C. From the depositional units and topographic configurations of these major blocks, a reasonable inferenceis that the rock avalanche more or less kept the order of the rock sequences in its scarp.

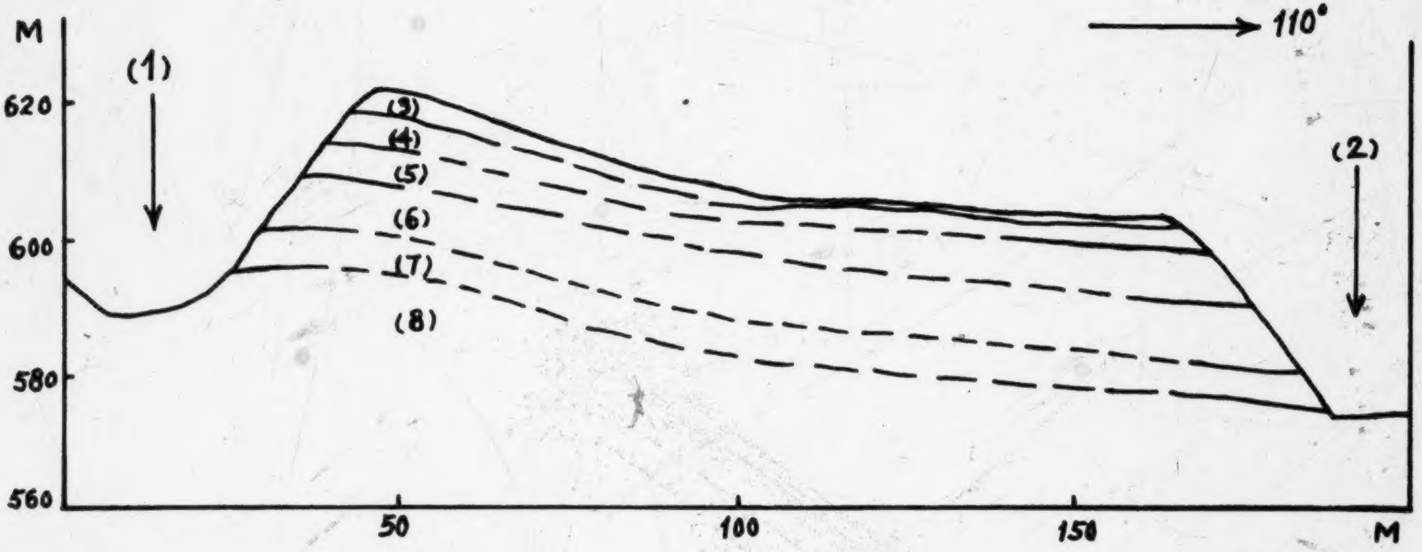

M
620
600
580
560
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
→ 110°
50
100
150
M

Figure 2.17 Same Depositional Units on Both Sides of Block 1, Along Line A-A'on Fig. 2.4

(1) Turbid Creek; (2) Dusty Creek; (3) 1984 deposits; (4)-(6) 1963 deposits: (4) Grey unit; (5) Brown unit; (6) Green-grey unit; (7) Old rock avalanche deposits; (8) Basement rock.

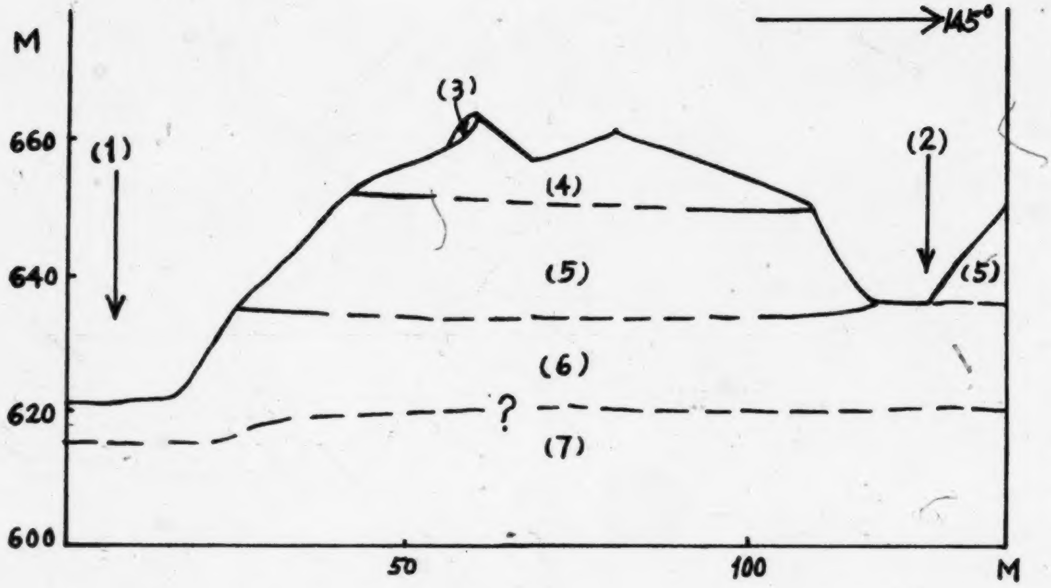

M
145°
660
640
620
600
(1)
(2)
(3)
(4)
(5)
(5)
(6)
?
(7)
50
100
M

Figure 2.18 Same Depositional Units on Both Sides of Block 2, Along Line C-C' on Fig. 2.4

(1) Turbid Creek; (2) Dusty Creek; (3) 1984 deposits; (4)-(6) 1963 deposits: (4) Upper grey unit; (5) Brown unit; (6) Lower grey unit; (7) Basement rock.

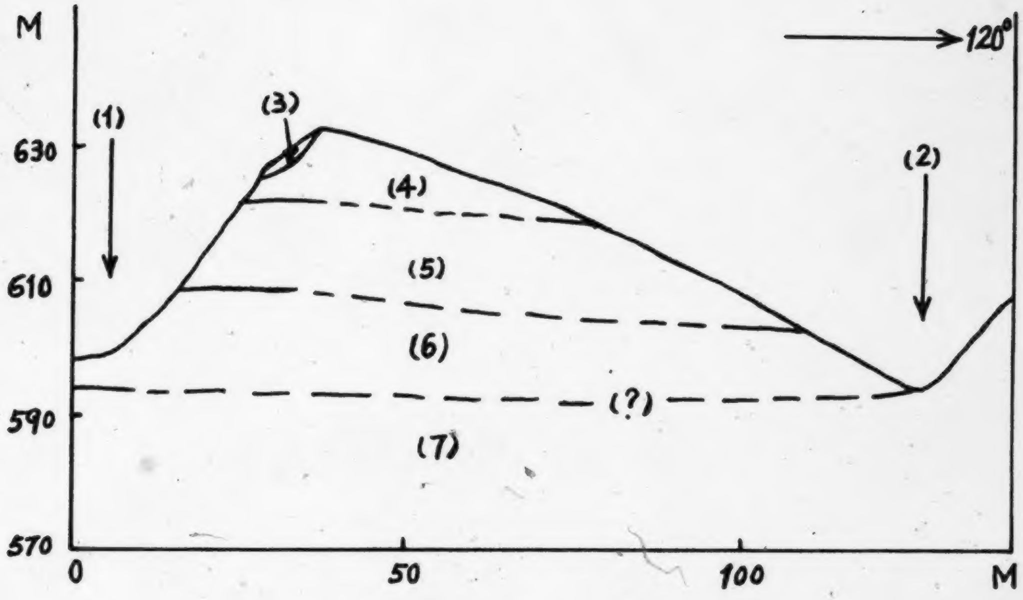

M
→120°
(1)
(3)
(2)
(4)
(5)
(6)
(?)
(7)
630
610
590
570
0
50
100
M

Figure 2.19 Same Depositional Units on Both Sides of Block3, Along Line D-D' on Fig. 2.4

(1) Turbid Creek; (2) Dusty Creek; (3) 1984 deposits; (4)-(6) 1963 deposits: (4) Purple unit; (5) Dark brown unit; (6) Green-grey unit; (7) Basement rock.

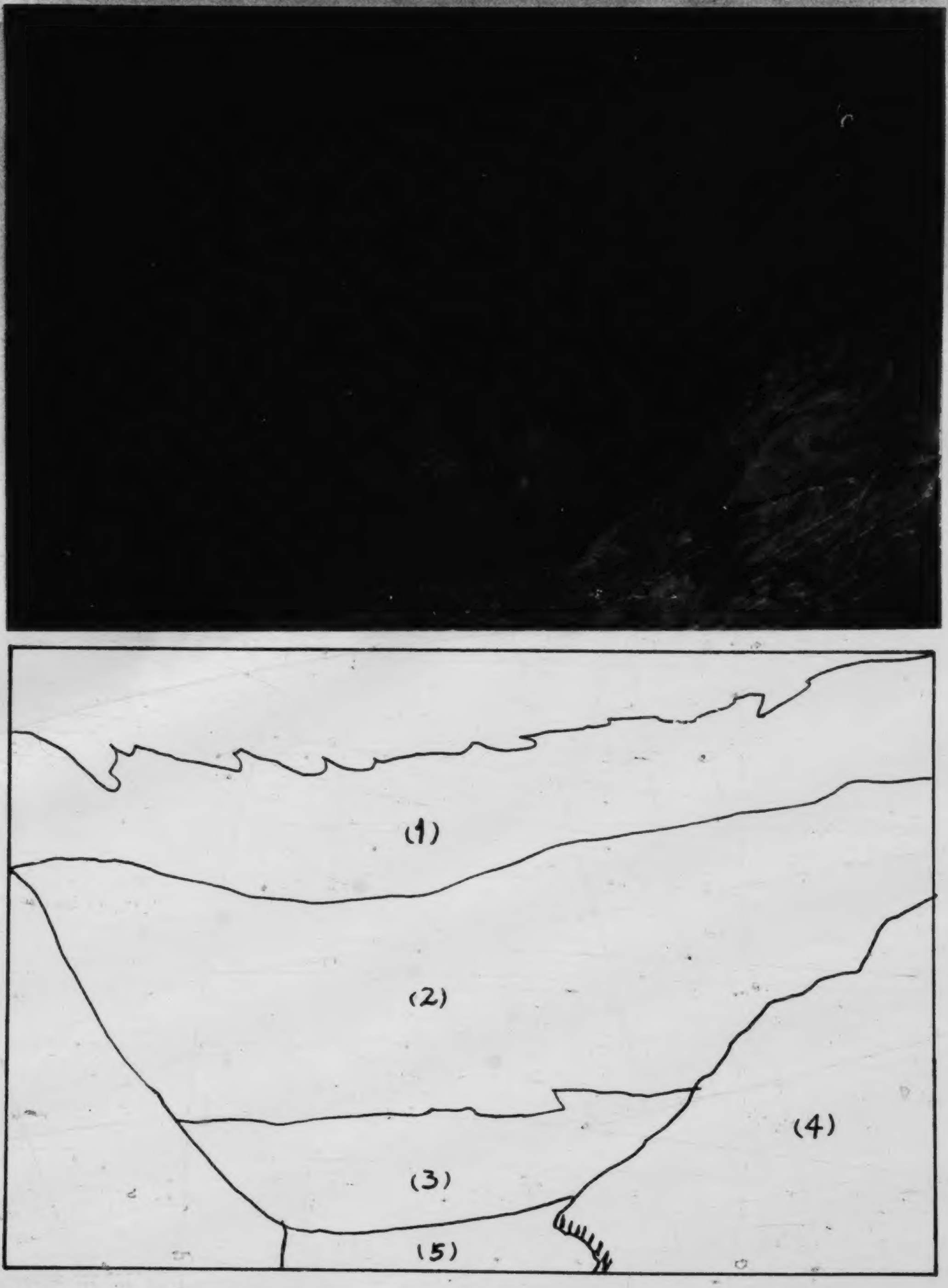


Figure 2.20 Depositional Units on the other Side of Block 3, Location indicated on Fig. 2.4

(1)-(3) 1963 deposits: (1) Purple unit; (2) Dark brown unit; (3) Green-grey unit; (4) Basement rock; (5) Dusty Creek.

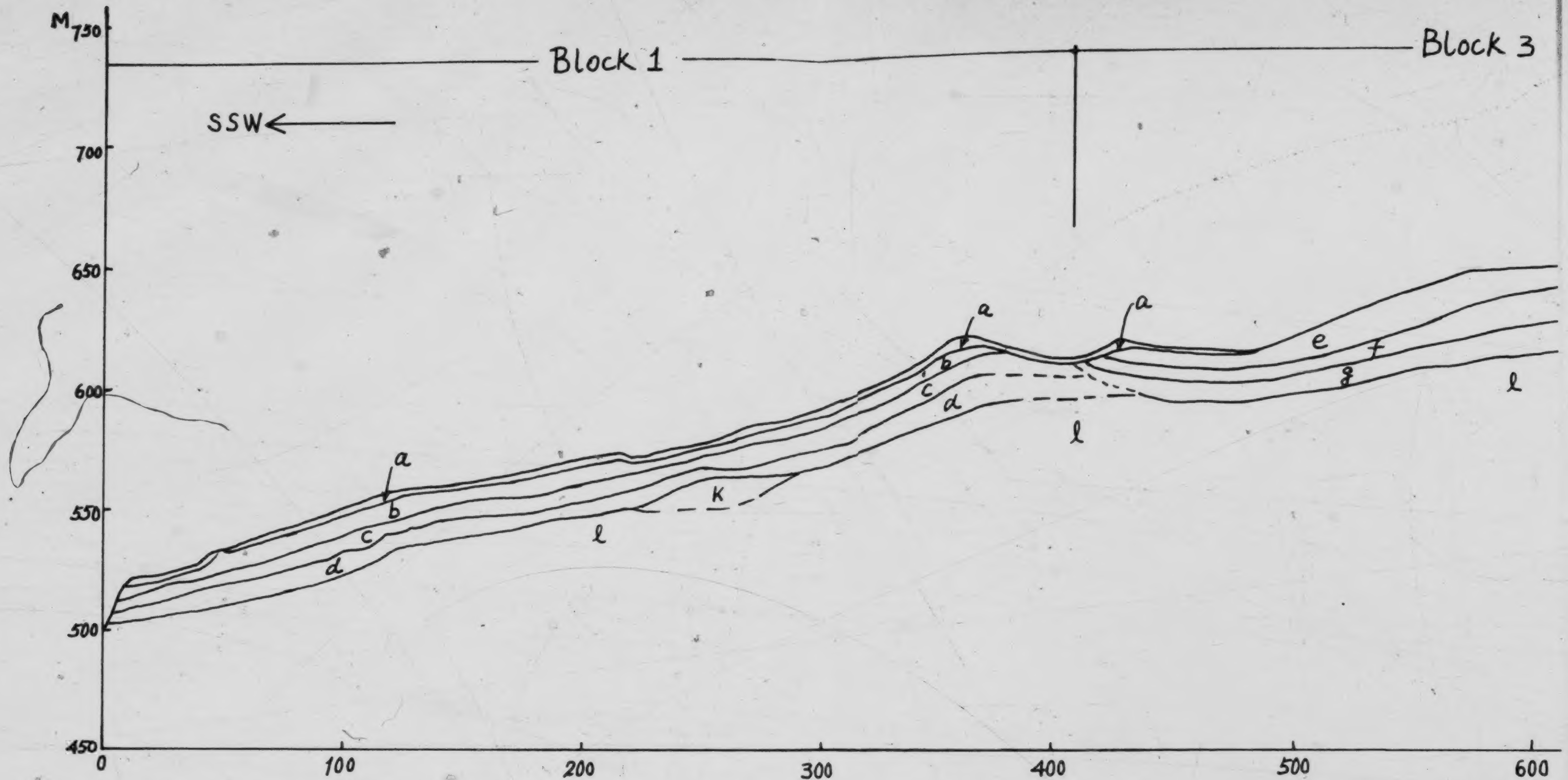

M
750
700
650
600
550
500
450
Block 1
Block 3
SSW
a
b
c
d
e
f
g
k
l
0
100
200
300
400
500
600

Figure 2.21 Different Depositional Unit

Along Line E-E' on Fig

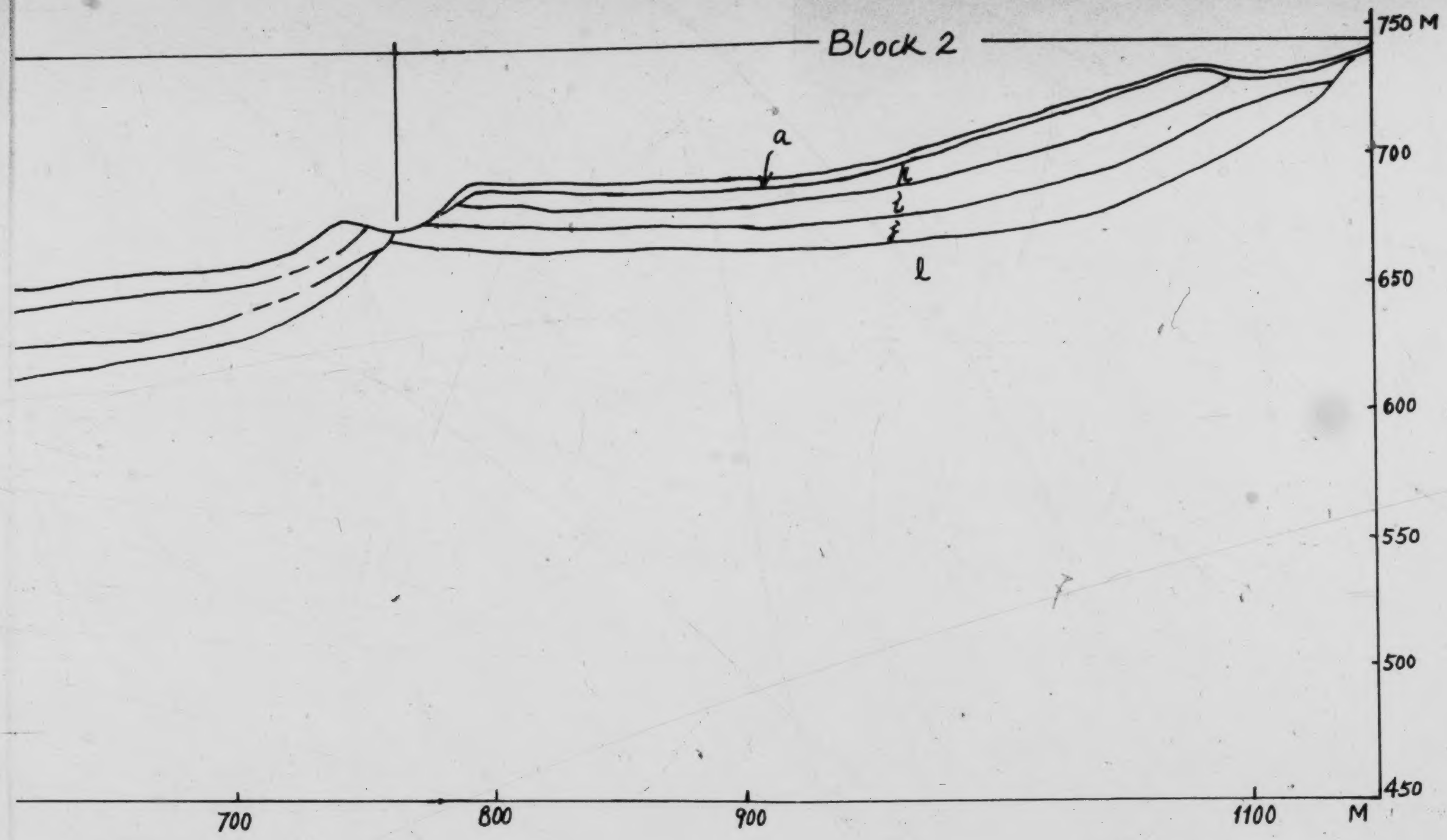
a-1984 deposits; b-j 1963 deposits: b-g

unit, d-green-grey unit (in block 1);

brown unit, g-green-grey unit (in bloc

unit, i-brown unit, j-lower grey unit (

rock avalanche deposits; l-basement roc


Block 2
a
k
i
j
l
750 M
700
650
600
550
500
450
700
800
900
1100
M

s in Different Blocks

. 2.4

rey unit, c-brown

e-grey unit, f-dark

3); h-upper grey

in block 2); k-old

.

2.4 Movement Pattern and Results of the 1963 Rock Avalanche

5×10^6 m^3 volcanic rock was involved in the rock avalanche and travelled 2.4 km. It should be interesting to trace the trajectory of the movement of the rock mass and to determine the results that the rock avalanche caused.

2.4.1 Trajectory of the 1963 Rock Avalanche

1. The general movement path

From the phenomena shown on the aerial photographs taken in August 1964, especially the forest trimline, and the field investigation conducted in the Summer of 1986, the general movement path of the 1963 rock avalanche has been briefly figured out as following.

At the very beginning of the rock avalanche, a huge block of tuff breccia and columnar-jointed dacite detached from the north-west slope of Dusty Creek and slid towards the southeast (left bank of Dusty Creek) to the course of Dusty Creek. It slid across Dusty Creek and impacted against the southeast side of Dusty Creek valley. During the impact, the slide mass might be partly broken, and the movement directed towards the opposite side of the creek valley. Then the mass moved in a curve along the right bank of Dusty Creek, and swung back to the opposite (southeast) side of the valley again at the end of the curve. The broken mass impacted the southeast slope again and shifted movement direction. Finally the rock mass rushed into the course of Turbid Creek and came to rest in the gentle valley.

2. Movement trajectory of blocks

As mentioned previously, the accumulation area consists of three separated huge blocks which were recognized by their different topographic configurations and depositional units. The rock avalanche contained three separated blocks, and these blocks moved one after another. From the characteristics of the deposits and their boundaries (Figs. 2.5 and 6), block 3 was the last one which came to rest in the space between blocks 1 and 2.

It seems likely that block 1 rushed into Turbid Creek and came to rest first at the space between present confluence of Dusty and Turbid Creeks and the downstream edge of block 3 (Fig. 2.22 a) in Turbid Creek valley. Then block 2 came to rest in Turbid Creek valley. A part of the debris travelled upstream in Turbid Creek. So the deposits formed an arc-like shape in plane (Fig. 2.22 b). Finally block 3 came and filled in the open space between blocks 1 and 2, leaving two unfilled up gully-like depressions at its two ends (Fig. 2.22 c).

2.4.2 The Results of the 1963 Rock Avalanche

Evidence of the main results of the 1963 rock avalanche comes from: pre- and post-slide aerial photo comparison, field investigation and interviewing loggers.

It is obvious that the debris of the 1963 rock avalanche did not reach the logging road, as the loggers (Charlie Deminger, John Thompson and Peter Thomson) who were

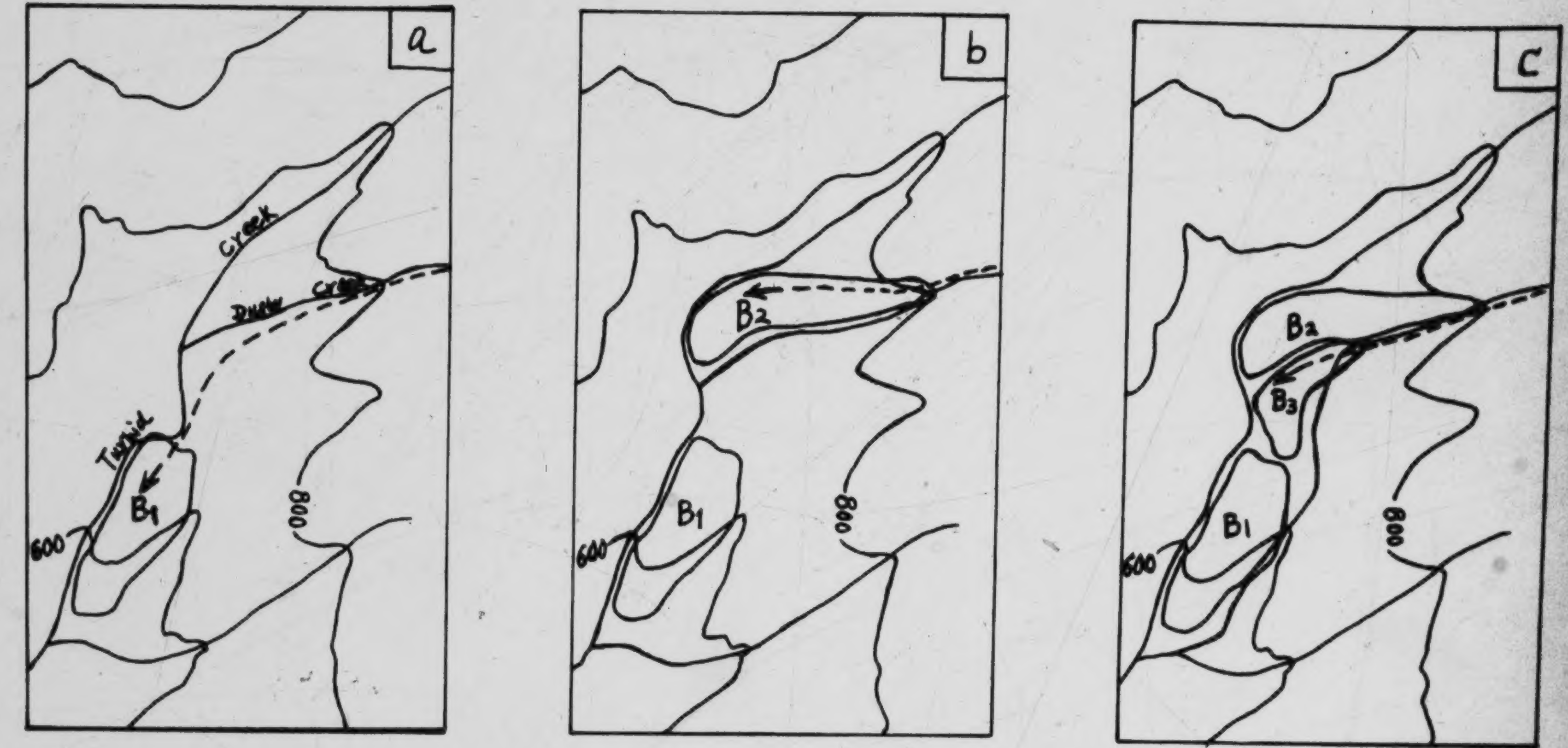

a
Creek
Creek
B1
600
800
b
B2
B1
600
800
c
B2
B3
B1
600
800

Figure 2.22 Debris Deposition Process, B1 Block 1, B2 Block 2, B3 Block 3.

interviewed by the author pointed out that no damage to the road or the bridge occurred in the Summers of 1963 and 1964. It seems likely that the debris of the 1963 rock avalanche terminated at the downstream end of block 1, as no significant deposits of this rock avalanche have been found after this point.

The main results of the 1963 rock avalanche are the obstruction of Turbid and Dusty Creeks and the change of the course of Dusty Creek.

1. The obstruction of Turbid and Dusty Creeks

It is still evident that blocks 1 and 2 blocked Turbid Creek when they came to rest in the course of the creek.

Block 1 occupied part of the pre-slide course of Turbid Creek (from the comparison of the pre- and post-slide aerial photos) and totally blocked Turbid Creek. Later, Turbid Creek cut through the deposits near the edge of block 1 and formed its present course. Fig. 2.23 shows the remnant of block 1 on the present right bank of Turbid Creek. As a result , Turbid Creek has moved 200 m westwards.

Block 2 consists of two parts, the major part on the left bank of Turbid Creek extends upstream into Dusty Creek (Fig. 2.8), the smaller part is between the present course of Turbid Creek and No Name Creek (Fig. 2.24). Turbid Creek was blocked by block 2 but cut through the deposits and formed its present course.

Block 3 blocked Dusty Creek and caused the shift of the confluence of Dusty Creek and Turbid Creek.

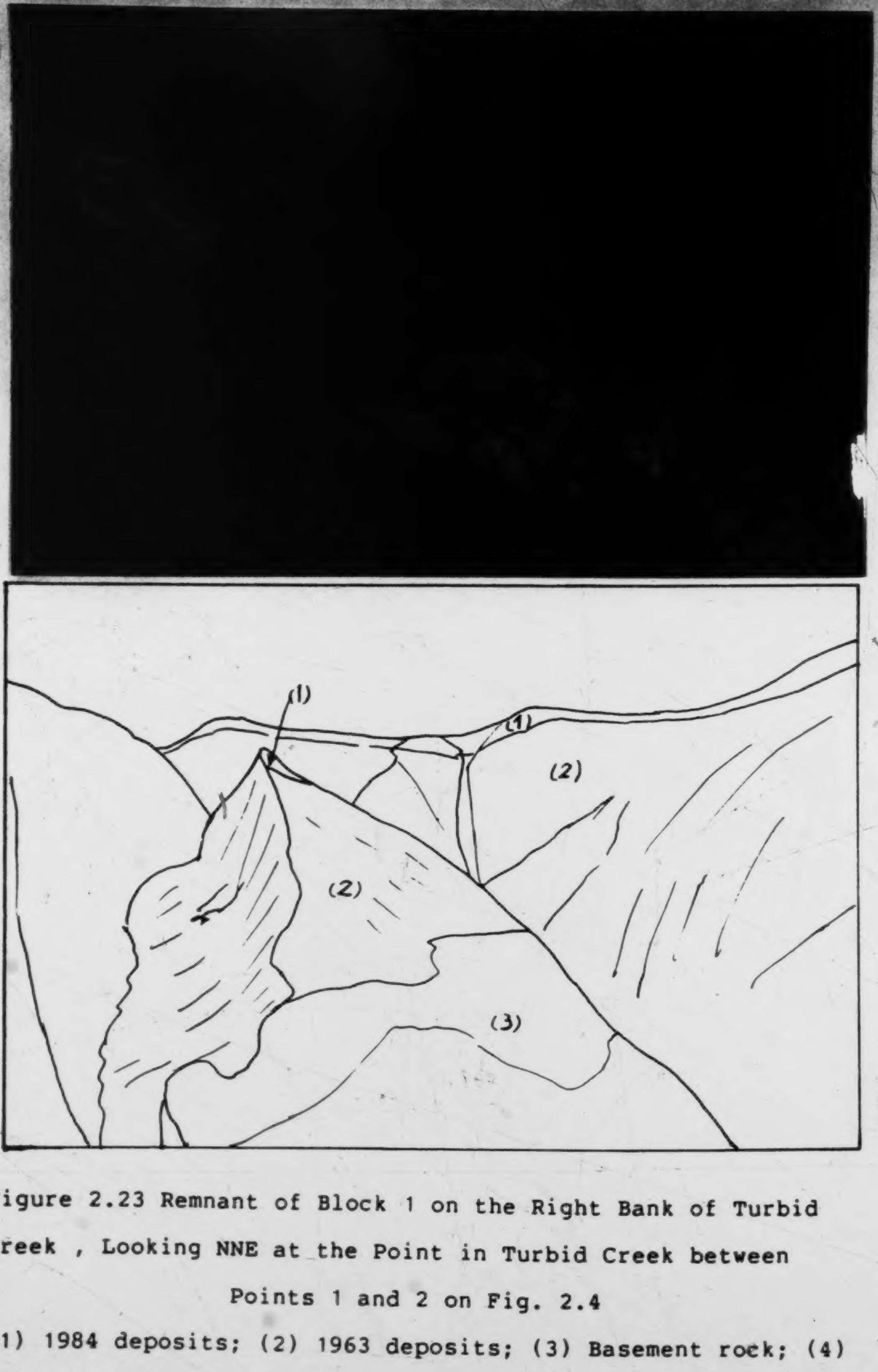


Figure 2.23 Remnant of Block 1 on the Right Bank of Turbid Creek , Looking NNE at the Point in Turbid Creek between Points 1 and 2 on Fig. 2.4

(1) 1984 deposits; (2) 1963 deposits; (3) Basement rock; (4) Turbid Creek.

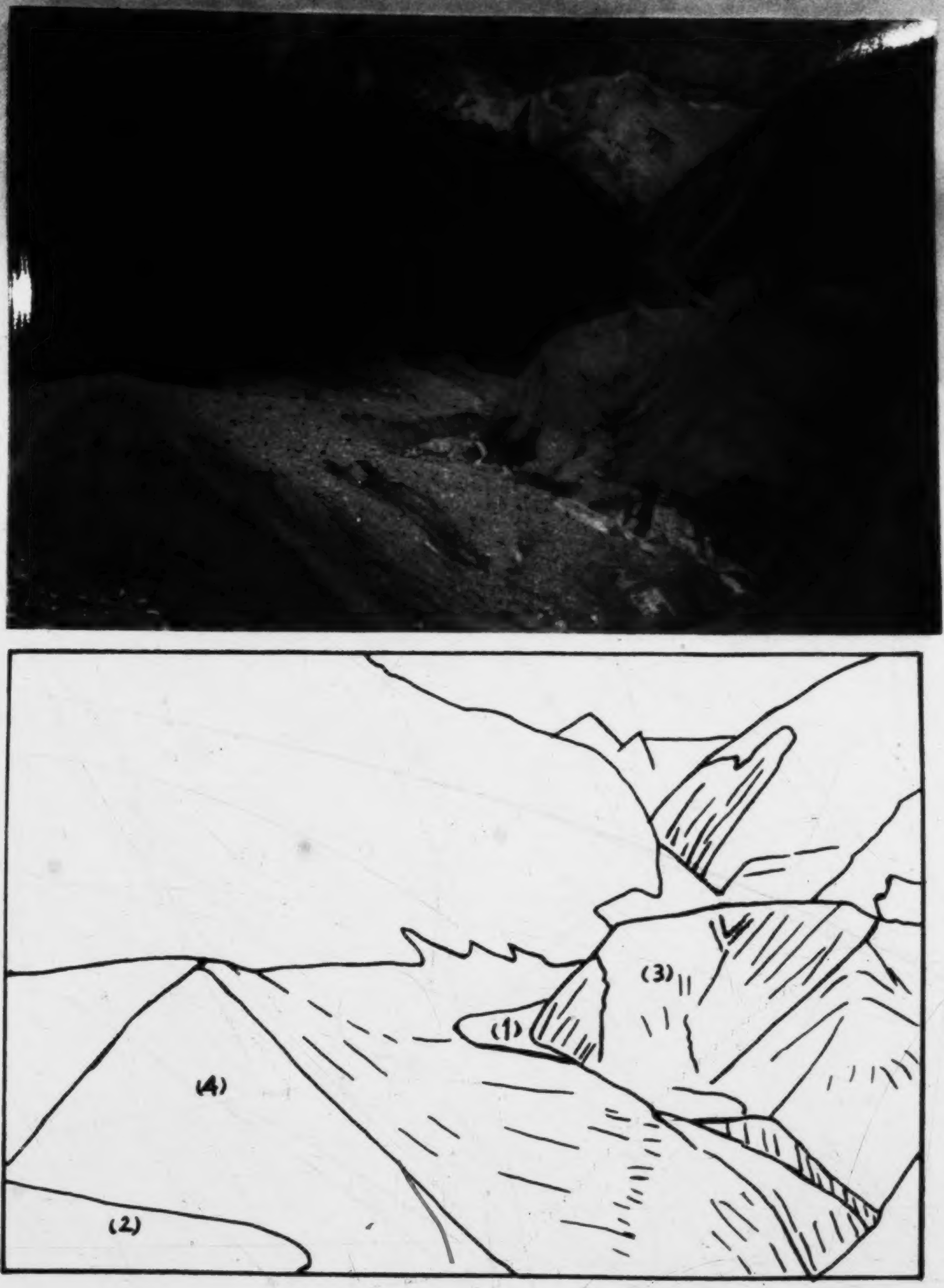


Figure 2.24 Small Part of Block 2, Looking NNE at Point 13 on Fig. 2.4

(1) Turbid Creek; (2) No Name Creek; (3) Main part of block 2; (4) Small part of block 2.

2. The shift of the confluence of Dusty and Turbid Creeks

The pre-slide aerial photographs (photos BC 424-30, 31) show the confluence of Dusty and Turbid Creeks located at the boundary of blocks 2 and 3 where there is now significant seepage (Fig. 2.25).

It is evident that present confluence of Dusty and Turbid Creeks is about 1 km downstream from the pre-slide confluence of these two Creeks (Fig. 2.26).

In summary, a large rock avalanche occurred in the head area of Dusty Creek most likely in July 1963. The event included three separated blocks which detached from the source area and travelled downstream one after another. These blocks were partly broken, but kept the essential order of the rock sequences. As a result, the accumulation area mainly consists of three separated blocks which have different stratigraphic units and obvious boundaries between them. Turbid and Dusty Creeks were blocked and their stream courses were shifted, the confluence of these two creeks was moved about 1 km downstream. The debris did not reach the logging road, and might terminate at the downstream edge of block 1. The 1963 rock avalanche travelled as a slide differing from the 1984 event downstream, in the main stream course of Turbid Creek.

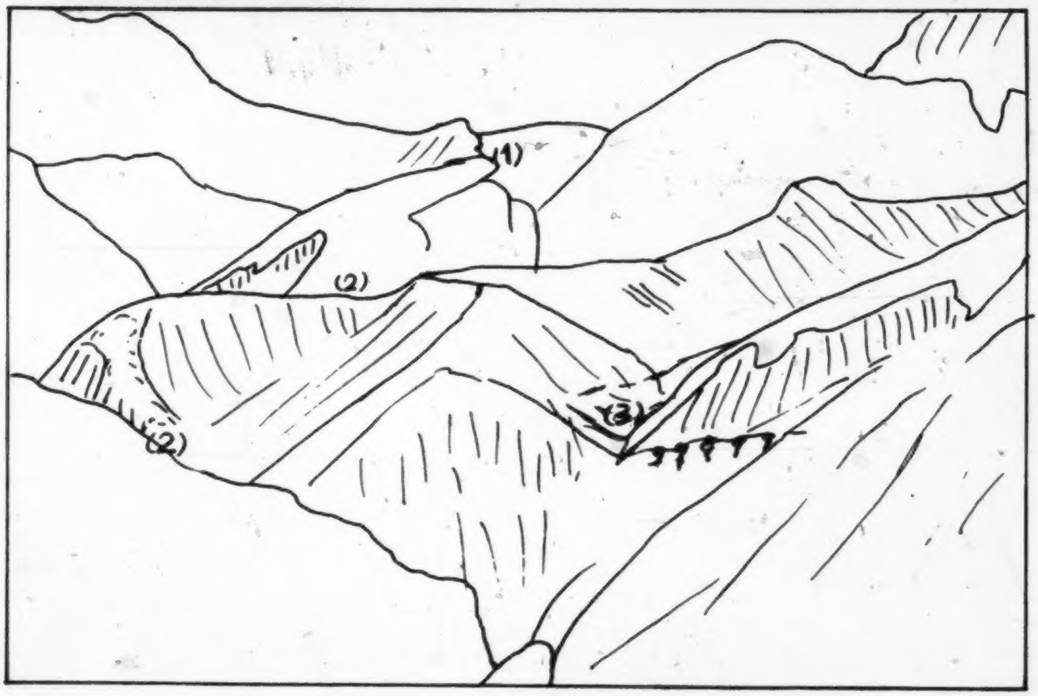


Figure 2.25 Seepage Revealing the Pre-slide Confluence,

Taken at Point 14, Looking NEE

(1) Source area of 1984 rock avalanche; (2) Turbid Creek;

(3) Pre-slide confluence of Dusty and Turbid Creeks.

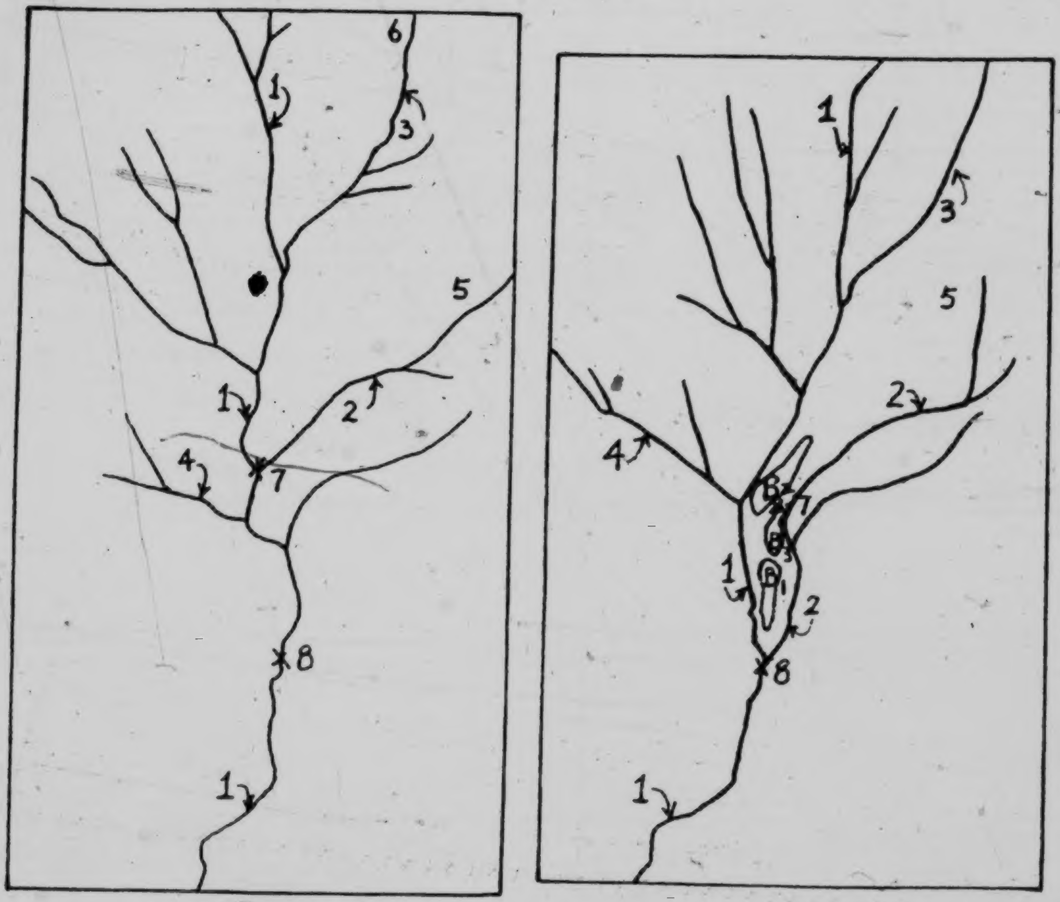


Figure 2.26 Shifting of Confluence and Diversion of Dusty Creek Revealed by Air Photos (BC424-31, and BC5103-131 Taken in 1947 and 1964 Respectively)

1-Turbid Creek, 2-Dusty Creek, 3-Avalanche Creek, 4-No Name Creek, 5-Source Area of the 1963 Rock Avalanche, 6-Source Area of the 1984 Rock Avalanche, 7-Pre-slide Confluence of Turbid and Dusty Creeks, 8-Present Confluence.

3. ROCK AVALANCHE AND DEBRIS FLOW IN 1984

3.1 Introduction

Another rock avalanche took place on Mount Cayley in 1984. This event is very different from the 1963 rock avalanche. The 1984 event was studied in detail in the summer of 1986. Six block samples of volcanic tuff were collected from the rupture surface and tested in laboratory. The results are presented in this chapter and the next.

The rock avalanche was initiated about 4 PM. local time on June 28, 1984 on the north side slope above Avalanche Creek, a small tributary of Turbid Creek (Fig. 3.1). A block of tuff breccia, lapilli and jointed dacite 200 m in length, 300 m in width, and up to 150 m in depth detatched from the rupture surface and slid southwards. The rock mass impacted the south-east side of Avalanche Creek and broke up. Then, the slide debris was confined to the valley of Avalanche Creek till it overtopped the small dividing ridge at the confluence of Avalanche and Turbid Creeks. Turbid Creek was dammed by the rock avalanche debris at the confluence. Mud and debris surges were generated by the breaching of temporary dams. The surges travelled and dammed Turbid Creek downstream and entered the Squamish River after further dams created by mud and debris flows burst. The area influenced by the avalanche is 6.2 km in length, 250 m in width and slopes at 12 ° from the crown at 1350 m to the tip at 140 m.

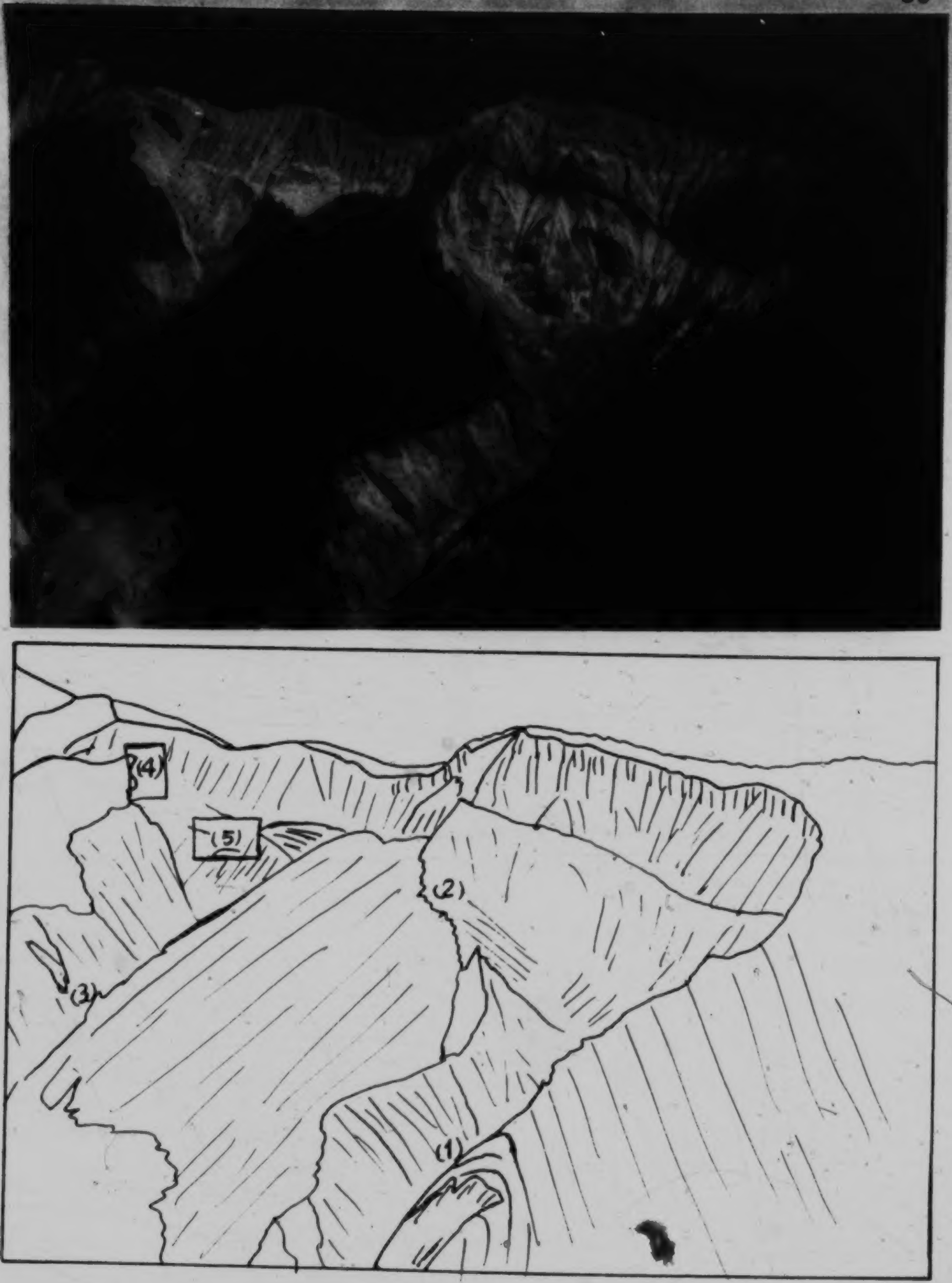


Figure 3.1 Location of the 1984 Rock Avalanche (1) Dusty Creek; (2) 1963 rock avalanche scarp; (3) Avalanche Creek; (4) 1984 rock avalanche scarp and location of Fig. 3.2; (5) Location of Fig. 5.2.

The two types of slope movements in the 1984 event on Mount Cayley produced two different deposits, slide deposits, and debris flow deposits. The former occur at the confluence of Avalanche and Turbid Creeks, the latter along the valley of Turbid Creek 300 m after the confluence. These deposits and special phenomena created by debris flow have recorded the main characteristics of the 1984 event.

This chapter is devoted to the descriptions of the special phenomena with brief interpretations.

3.2 Source Area

3.2.1 Introduction

The source area of the 1984 rock avalanche is on the north side of Avalanche Creek at the crest of the creek valley. Avalanche Creek is a small tributary of Turbid Creek, located between Dusty Creek to the south and Turbid Creek to the north. As the scarp is inaccessible, the rock sequences and the weak zones were observed at a distance from the opposite side of the creek.

3.2.2 Rock Sequences

The rock succession exposed in the source area is briefly described as following (from bottom to top) (Fig. 3.2).

1. Unit 1, Basement rock, granodiorite, quartz diorite.
2. Unit 2, Browncolumnar-jointed dacite, 60 m.

3. Unit 3, Brown columnar-jointed dacite and grey-white lapilli tuff and tuff breccia, 80 m.
4. Unit 4, Dark brown columnar-jointed dacite, 100 m and grey tuff 40 m.
5. Unit 5, Purple tuff lapilli 80 m, light yellow tuff breccia 30 m and grey tuff 20 m.

3.2.3 Weak zones

The main weak zones are

1. The boundary between the basement rock and the volcanic rock. It is a pre-eruption ground surface dipping south-east at about 22°
2. Joints.
3. Tuff layers.

The boundaries of the 1984 rock avalanche developed along these weak zones. For example, the main scarp developed along aset of planar, south-west trending, nearly vertical joints. The rupture surface is located at a weak tuff layer (Fig. 3.3).

3.3 Characteristics of Displaced Masses

3.3.1 Introduction

The deposits of the 1984 event can be divided into rock avalanche deposits and debris flow deposits. The former occur at the confluence of Avalanche and Turbid Creeks. The latter line the valley of Turbid Creek 300 m downstream from

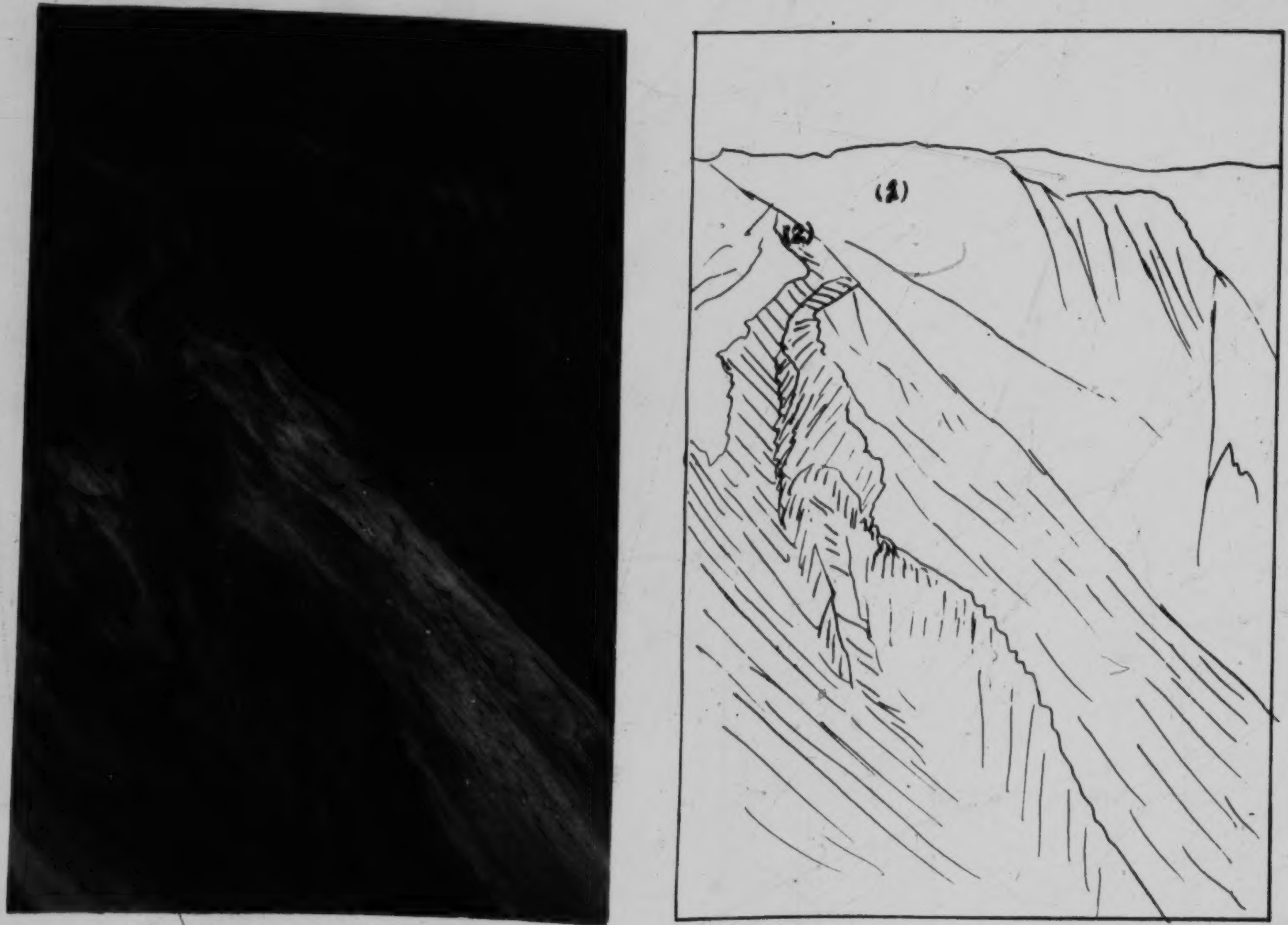


Figure 3.2 Rock Sequences in Source Area, Location shown on Fig.3.1

(1)-Bedrock unit 5-Purple lapilli and tuff; (2) Sampling site.

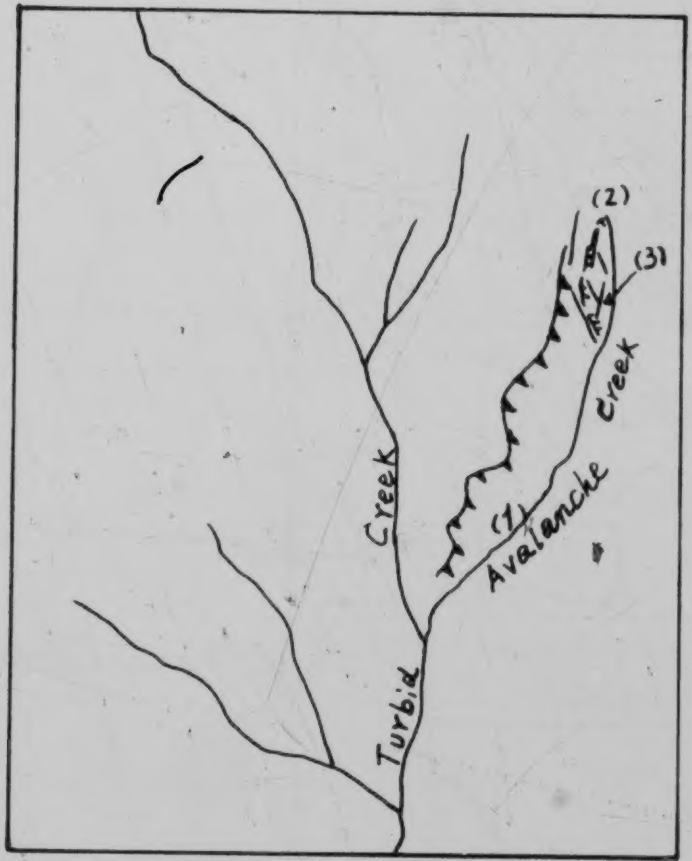

(2)
(3)
(1)
Creek
Turbid
Avalanche
Creek

Figure 3.3 A General Map of the 1984 Rock Avalanche Source Area

(1) Pre-eruption ground surface; (2) Nearly vertical joints; (3) Weak tuff layer.

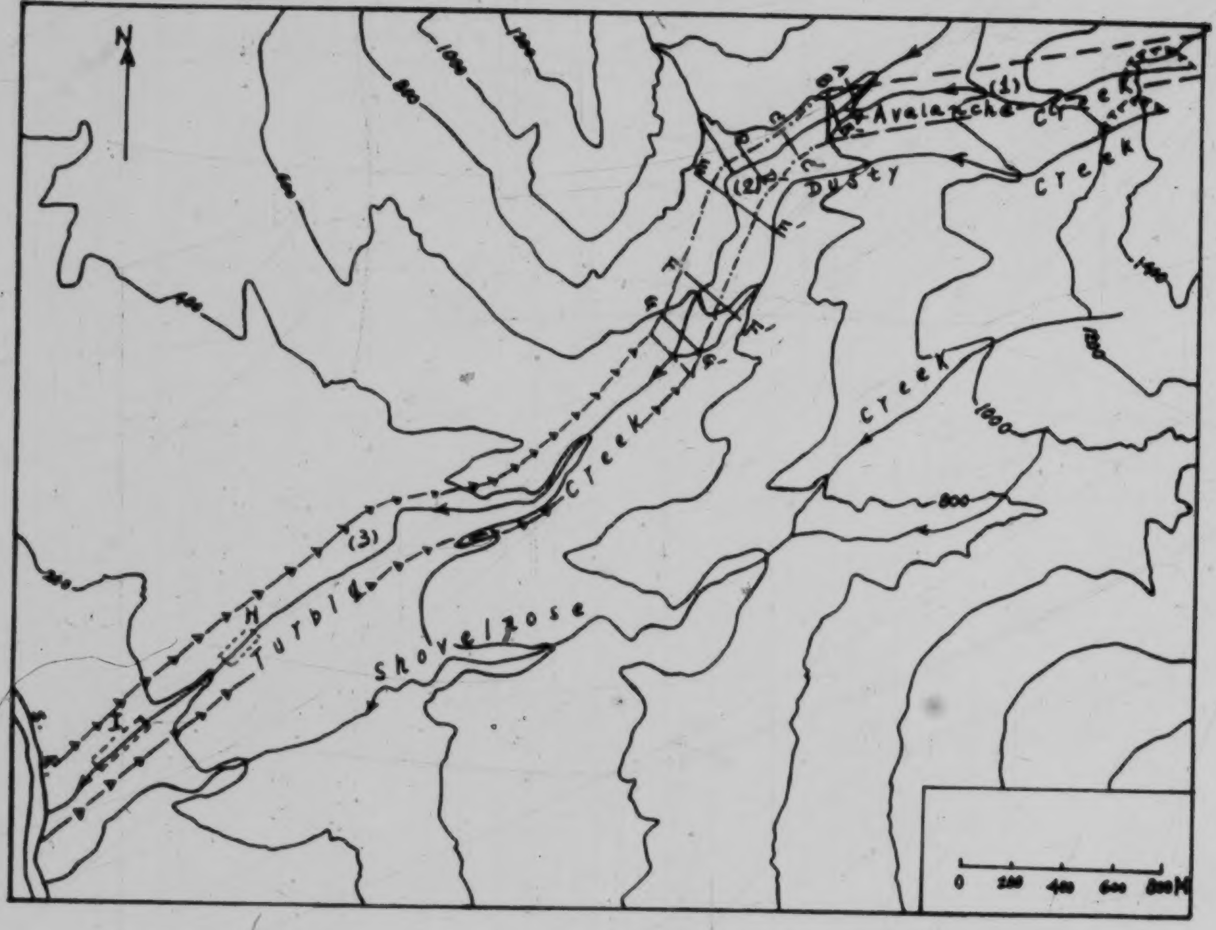
the confluence of Avalanche and Turbid Creeks.

The rock avalanche deposits are different from the 1963 rock avalanche deposits, without distinct depositional units. The debris flow deposits are totally different from the 1963 rock avalanche deposits.

3.3.2 Map of Deposits

On a map of the 1984 deposits (Fig. 3.4) three areas have been recognized, the upper stream area, middle stream area and lower stream area. The upper stream area, at the confluence of Avalanche and Turbid Creeks, 350 m long and 100 m wide contains rock avalanche deposits. The middle stream area from the end of the upper stream area to the present confluence of Dusty and Turbid Creeks contains viscous debris flow deposits. The lower stream area from the present confluence of Dusty and Turbid Creeks to the confluence of Turbid Creek and the Squamish River shows deposits from a mobile debris flow.

Thus, the deposits in the upper stream area are thick and rich in blocks and huge boulders. The deposits in the middle area are a thin, sticky blanket over the whole valley. The deposits in the lower stream area are very similar to the deposits created by a flood which carries lots of debris.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Avalanche Creek
Dusty Creek
Creek
Turbid Creek
Shovelnose
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Figure 3.4 Map of the 1984 Deposits

(1) Upper stream area; (2) Middle stream area; (3) Lower stream area; A-A', B-B'...G-G' Section lines; H-Location of Fig. 3.14; I-Location of Fig. 3.15.

3.3.3 Deposits in the Upper Stream Area

The 1984 rock avalanche deposits are at two sites, the right (north-west) bank and the centre of Turbid Creek 50 m upstream from the confluence of Avalanche and Turbid Creeks, and the left (south-east) bank of Turbid Creek 30-300 m downstream from the confluence of Avalanche and Turbid Creeks.

The deposits on the first site formed a part of the natural dam (Fig. 3.5). The present thickness of the deposits is 5-20 m. The deposits are light yellow breccia and purple lapilli up to 4 m across. The remainder of the dam in the centre of the creek is light yellow breccia. The deposits on the north-west bank are light yellow breccia and purple lapilli. These rock avalanche deposits could not be subdivided into distinct depositional units.

The terrace-like south-east bank of Turbid Creek 30-300 m downstream from the confluence consists of 15 to 30 m of the 1984 rock avalanche deposits (Fig. 3.6). No distinct depositional units were seen in these deposits.

Obviously, the 1984 rock avalanche deposits mainly consist of the special rocks, light yellow breccia and purple lapilli, which came from Unit 5 of volcanic rock in the source area, with lots of dacite blocks and boulders.

3.3.4 Deposits in the Middle Stream Area

Deposits of the 1984 event in the middle stream area are wide-spread on both sides of Turbid Creek (Figs. 3.7,

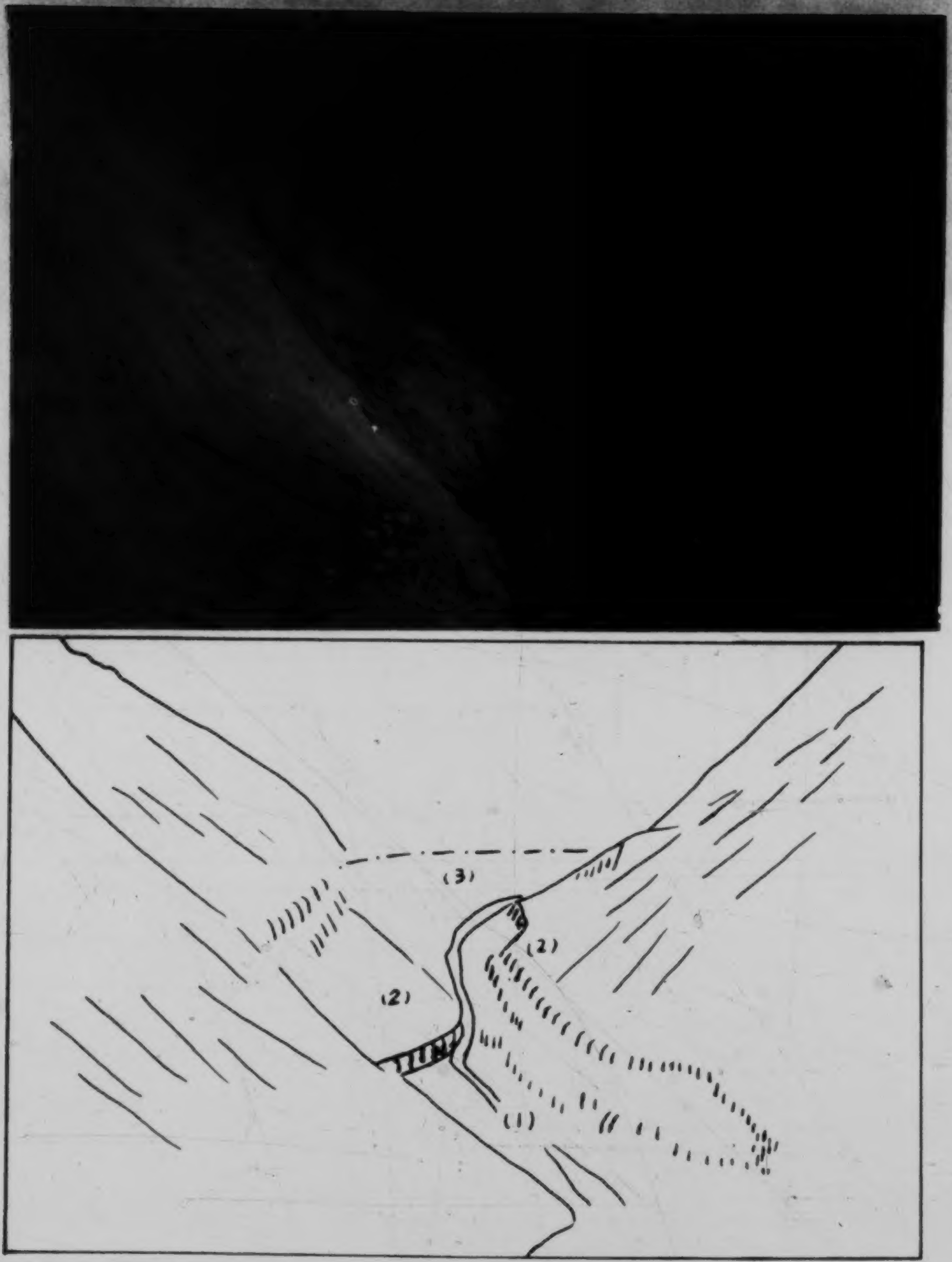

Figure 3.5 Remnant of Debris Dam, Along Line A-A' on Fig. 3.4

(1) Turbid Creek; (2) Remnant of debris dam; (3) Inferred top of the dam.

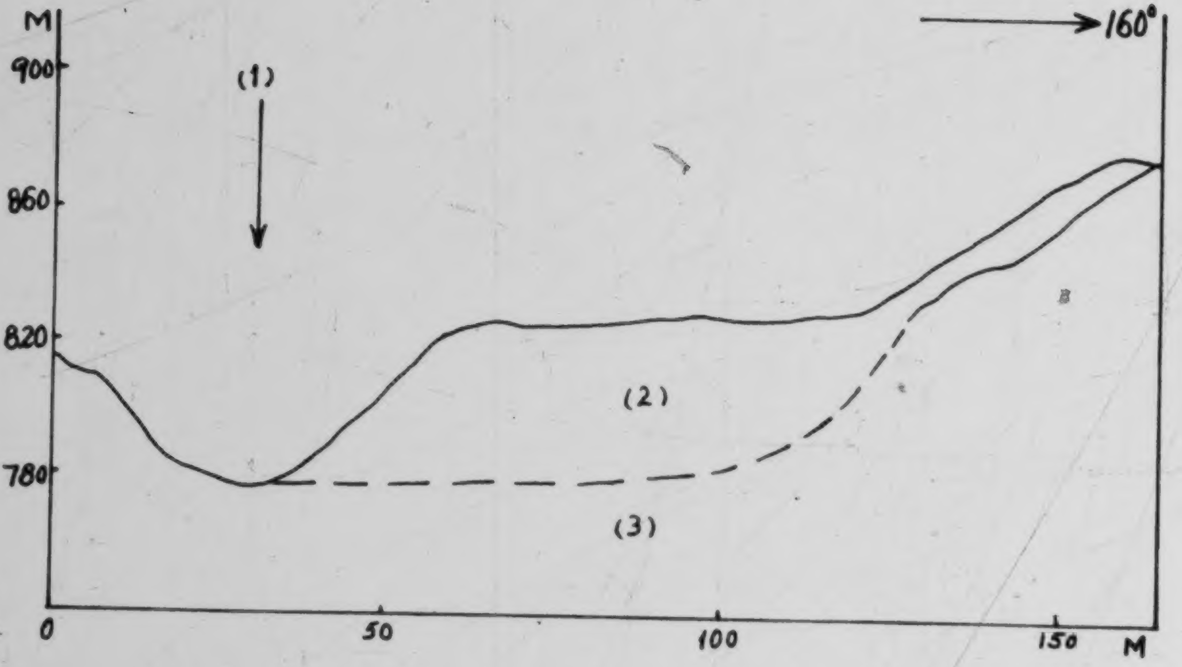

Figure 3.6 The 1984 Rock Avalanche Deposits, Along Line B-B' on Fig. 3.4

(1) Turbid Creek; (2) 1984 rock avalanche deposits; (3) Basement rock.

8, 9, 10, and 11). They consist of grey tuff, light yellow breccia, purple lapilli and brown dacite. Light yellow breccia and purple lapilli on the top of the deposits (Fig. 3.12) distinguish 1984 debris flow deposits from the 1963 rock avalanche deposits (brown dacite and grey or green-grey tuff).

Upstream the thickness of the deposits reaches 5-8 m (Figs. 3.7 and 3.8), but the average thickness is 4 m. Downstream the thickness of the 1984 debris rarely reaches 4 m, and often the thickness of the deposits in this area is only 0.5-2 m

The deposits of the 1984 event reached a large range of altitudes. In Figs. 3.9, 10 and 11, the lowest deposit is on the stream bed of the creek and the highest deposit is on the top of the escarpment of the 1963 rock avalanche deposits. The altitude difference is 43 m (Fig. 2.10), 34 m (Fig. 3.10) and 45 m (Fig. 3.9). Thin deposits (0.1-0.2 m) can be seen on the slopes between the bottom and the top of these escarpments with elevation differences of 40 m.

The blocks and the boulders in the deposits are supported by fragments or powder of grey tuff. Huge boulders on the upper surface of the deposit (Figs. 3.12 and 13) are surrounded by small blocks and particles. Many small particles are still stuck on the boulders.

These deposits are contributed by debris flow from the breaching of debris dams. They have the typical characteristics of debris flow deposits, small rock

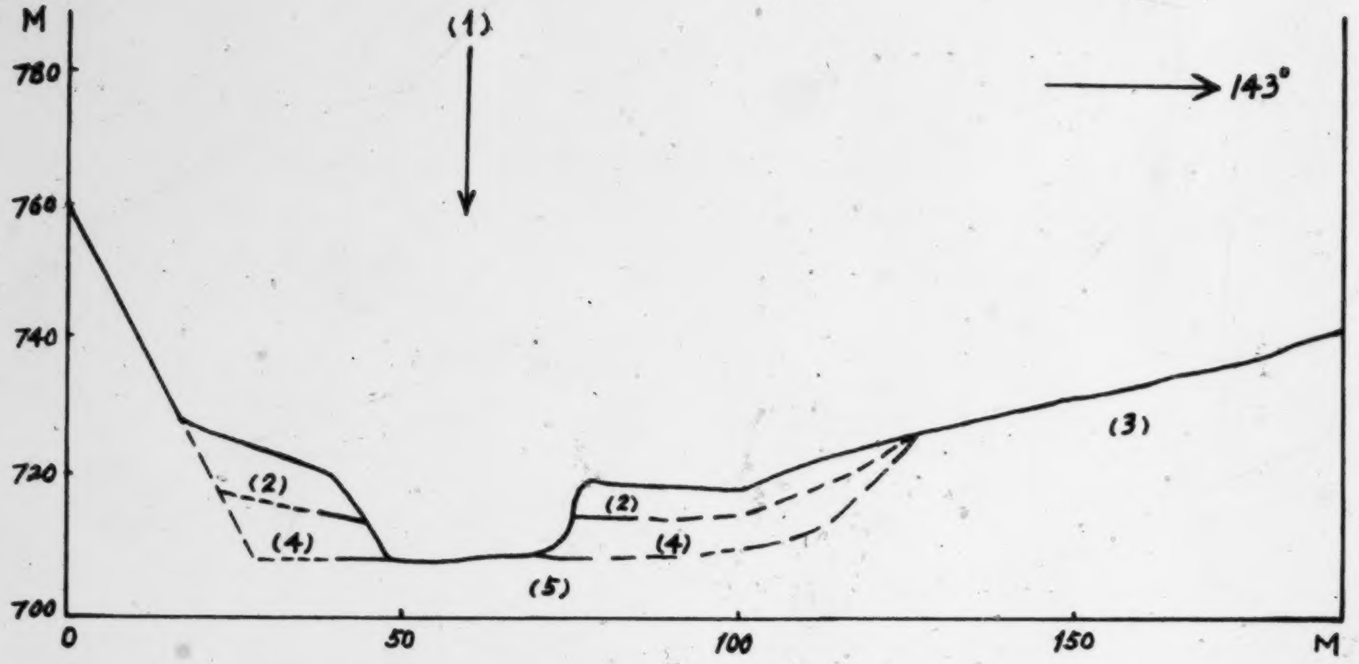
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Figure 3.7 1984 Deposits along Line C-C' on Fig. 3.4
(1) Turbid Creek; (2) 1984 debris flow deposits; (3) 1963 deposits; (4) Old rock avalanche deposits; (5) Basement rock.

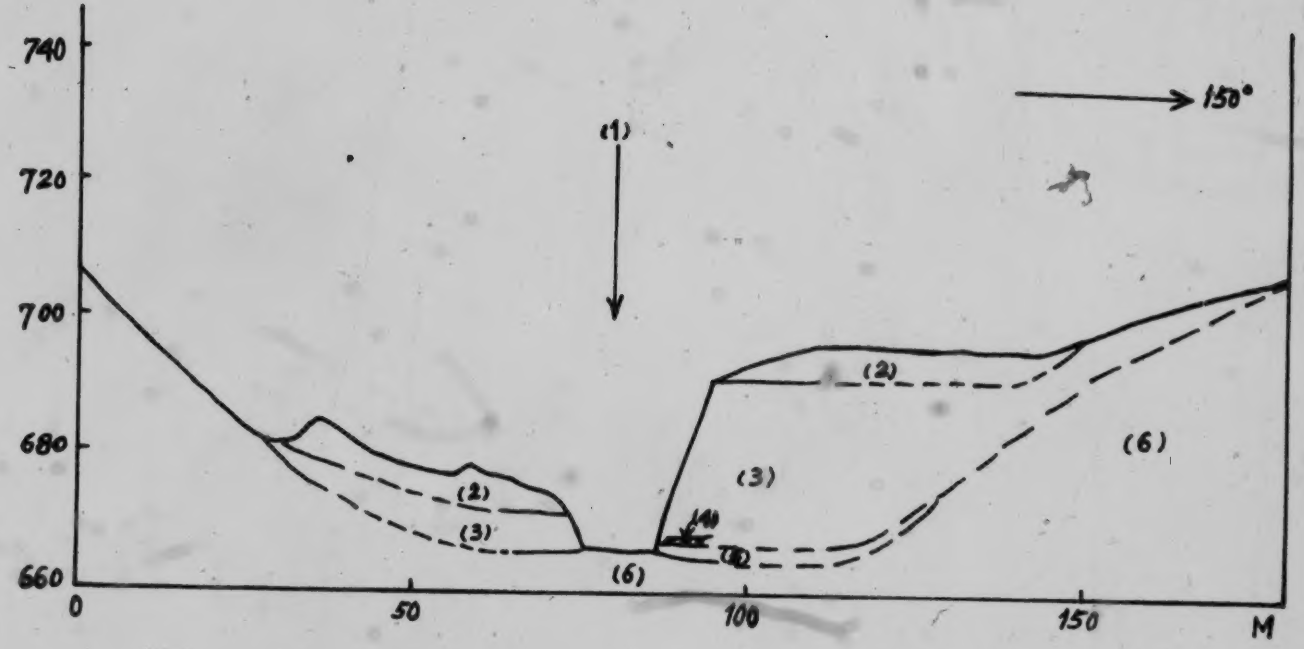
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Figure 3.8 1984 Deposits along Line D-D' on Fig. 3.4 (1) Turbid Creek; (2) 1984 debris flow deposits; (3) 1963 deposits; (4) Log; (5) Old rock avalanche deposits; (6) Basement rock.

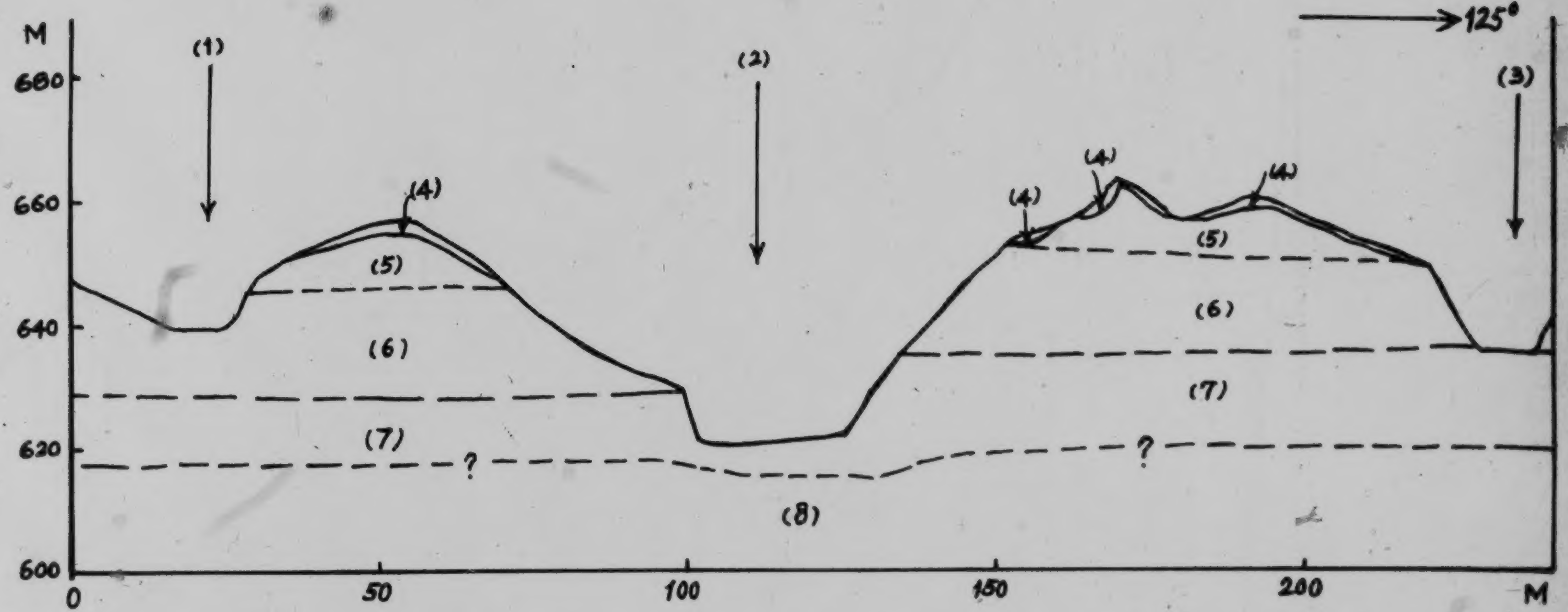
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Figure 3.9 1984 Deposits along Line E-E' on Fig. 3.4

(1) No Name Creek; (2) Turbid Creek; (3) Dusty Creek; (4) 1984 deposits; (5)-(7) 1963 deposits: (5) Upper grey unit; (6) Brown unit; (7) Lower grey unit; (8) Basement rock.

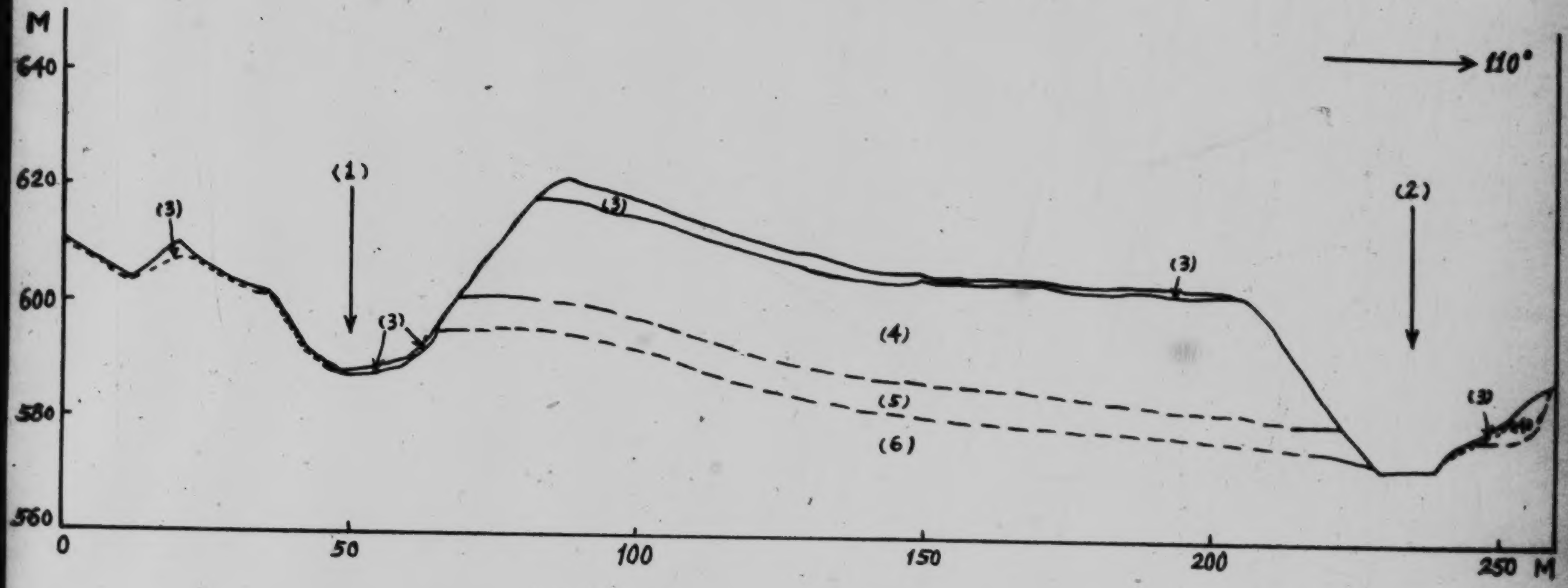
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Figure 3.10 1984 Deposits along Line F-F' on Fig. 3.4 (1) Turbid Creek; (2) Dusty Creek; (3) 1984 deposits; (4) 1963 deposits; (5) Old rock avalanche deposits; (6) Basement rock.

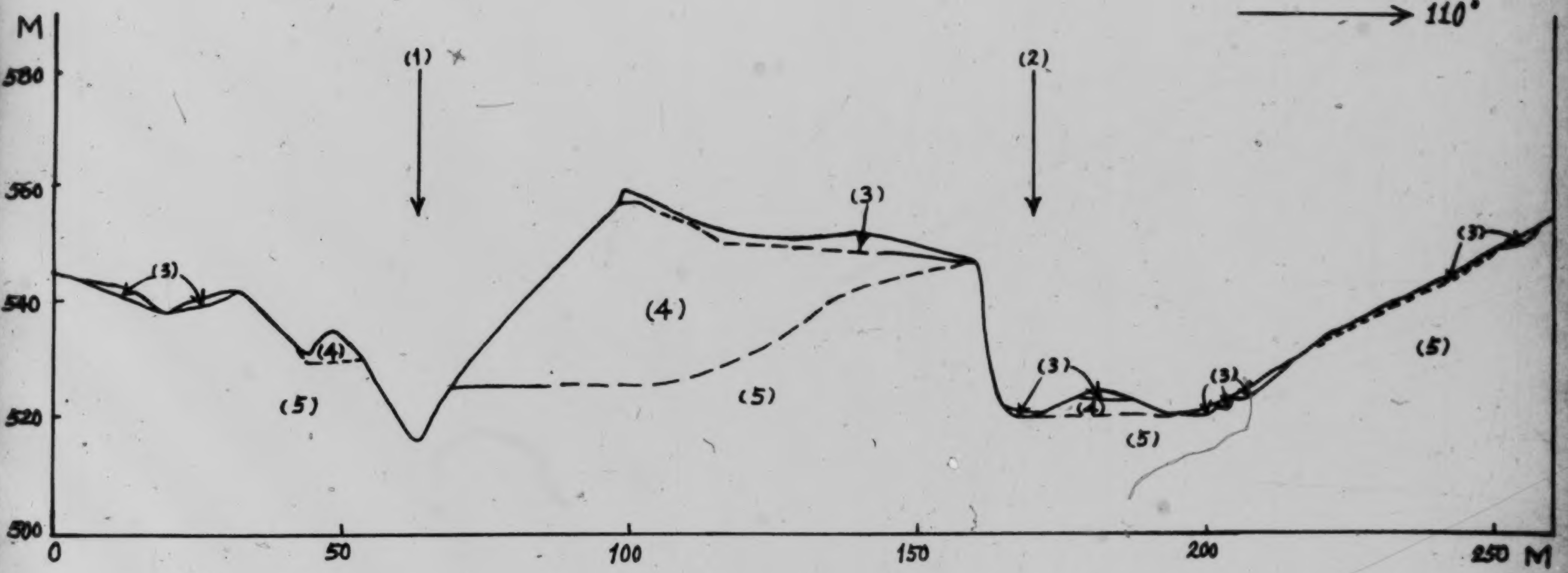

Figure 3.11 1984 Deposits along Line G-G' on Fig. 3.4

(1) Turbid Creek; (2) Dusty Creek; (3) 1984 deposits; (4) 1963 deposits; (5) Basement rock.

Figure 3.12 Typical 1984 Debris Flow Deposits at Point 4, Fig. 2.4

Figure 3.13 Huge Boulder on Top Surface at Point 4, Fig. 2.4

fragments and powder stick on the blocks and boulders, no layering, and huge boulders were carried and deposited on the top of the flows (Pierson and Costa 1987). These deposits mainly consist of light yellow breccia and purple lapilli.

3.3.5 Deposits in the Lower Stream Area

The deposits are confined to the valley of the creek up to 10 m above the bed of the stream (Figs. 3.14 and 3.15). The light-yellow breccia and purple lapilli still distinguish them from the older rock avalanche and debris flow deposits. Some differences have been observed between the deposits in the middle and the lower stream areas. The deposits in the middle stream area can reach 40 m above the stream bed, and their thickness can reach 2.0 m. The deposits in the lower stream area are confined to the valley of the creek. They are thin and not so viscous as the deposits in the middle stream area.

All the deposits of the 1984 event mainly consist of light yellow breccia and purple lapilli, distingishing the 1984 event deposits from older deposits, even the 1963 event deposits.

3.4 Special Phenomena Created by 1984 Event

Special phenomena have been observed in the field, high superelevations, uprooted trees, high mud spatters, airborne wood pieces, deposits on the south-east (left) bank slope of

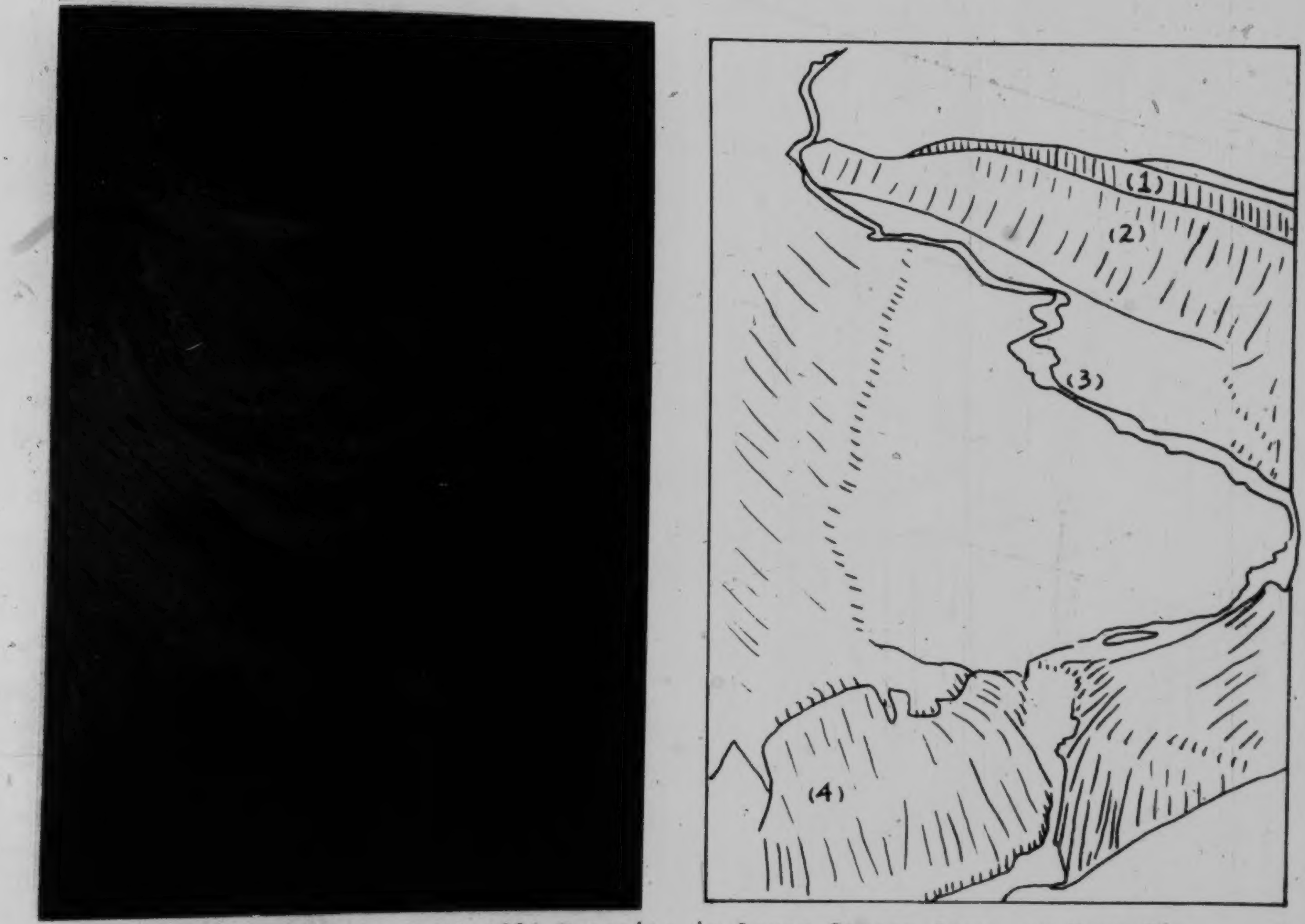

Figure 3.14 1984 Deposits in Lower Stream Area, as H on Fig. 3.4

(1) 1984 deposits; (2) Old rock avalanche deposits; (3) Turbid Creek; (4) Basement rock.

Figure 3.15 1984 Deposits in Lower Stream Area B, as I on Fig. 3.4 (Photo by Jaugelis)

Dusty Creek, damaged vegetation, huge boulders supported by small particles carried on the top surface of flows and deposited on the top of the escarpment, and light yellow rock belts. All these phenomena indicate the features of the event, the path of debris movements or velocities of the rock avalanche and the debris flow. These phenomena are described in detail in this section, interpreted in section 3.5., and finally velocity evaluations made in section 3.6.

3.4.1 Superelevation

Superelevation is created by flow around a bend, the flow reaches higher on the outside than on the inside.

When the 1984 rock avalanche debris entered the confluence of Avalanche and Turbid Creeks, it passed a gentle bend. On the outer (north) side of the bend, the debris reached 113 m above the stream bed, destroyed many trees and left debris (light yellow breccia) on the slope. On the inner (south) side of the bend the debris just reached 50 m above the stream bed and left debris deposits there (Figs. 3.16 and 3.5).

The difference of the altitudes, the superelevation, is 63 m. The width of the bend is 236 m. The radius of the curvature of the bend is 400 m .

3.4.2 Uprooted Trees

Trees have been uprooted on both sides of the creek at high altitudes with no or very thin debris deposits. The

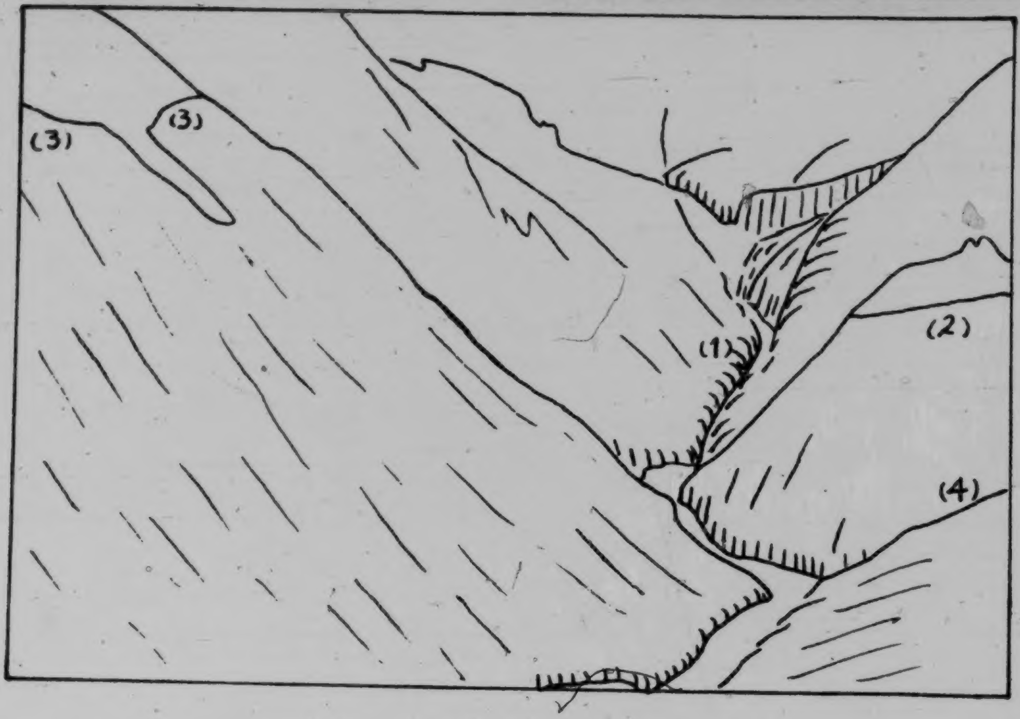

Figure 3.16 Superelevation Site 1

(1) Turbid Creek; (2) Deposits on the ridge; (3) Superelevation mark; (4) Avalanche Creek.

trees still have the top soil layer around their roots.

At point 1, on the north-west (right) bank of Turbid Creek, 38-34 m above the stream bed and 80 m from the centre of the stream horizontally (Fig. 2.4), eleven trees were uprooted and laid on the slope parallel to the direction of the valley (Fig. 3.17). The diameters of these fallen trees range from 0.5 to 1.5 m. Except for some mud spatters on the trunks and some small light yellow breccia and purple lapilli particles lodged in the fallen trees, no evidence that these trees were knocked down by the debris flow has been found. No huge boulders, or thick deposits around the trees account for the falls. On the contrary, the top soil layers with numerous small rock blocks which were deposited there many years ago were upset along with the fallen trees(Figs. 3.18 and 19).

Small branches and leaves had been stripped from the trunks of the uprooted trees for up to 10m from their bases. Above this point, branches and leaves remained on the trunks still green (Fig. 3.20) and alive. So these trees have fallen only a few years ago.

3.4.3 Mud Spatters on Trees

As shown on Figs. 3.21 and 22 mud spatters on trees located on the edge of the valley may reach up to 16 m above the ground. All mud spatters are found on the upstream side of the trees. As shown on Fig. 3.22, the upstream side of the trees are fully spattered by mud, but the downstream

Figure 3.17 Uprooted Trees, at Point 1 on Fig. 2.4

Figure 3.18 A Closer View of Fig. 3.17

Figure 3.19 Top Soil Layer Upset along Trees, at Point 1, Fig. 2.4

Figure 3.20 Green Branches and Leaves on Uprooted Trees, Point 1 on Fig. 2.4

side of these trees are mud free. The mud is mainly fine tuff and purple lapilli particles. The spattered trees are 20 m away from 1984 deposits.

It is evident that these mud spatters were generated by debris flow moving fast and in waves so that the mud spatters could reach 16 m above the ground.

3.4.4 Airborne Wood Pieces

In Fig. 3.23, two small pieces of wood stick in the trunk of a fallen tree. Their dimensions, 35 cm long by 15 cm wide and 10 cm thick, and 25 cm long by 5 cm wide and 5 cm thick give weights of 5 kg and 0.6 kg respectively. No huge boulders, nor thick deposits are found around this point, 200 m downstream from the uprooted trees on point 3. There are, however, impressions made on the trunk by small, flying stones. A reasonable interpretation would be these small pieces of wood were carried by strong winds into the trunk.

3.4.5 Deposits on Both Sides of Dusty Creek

The debris flow travelled over the escarpment located on the south-east side of the valley of Turbid Creek and some debris reached the opposite (south-east) side of the valley of Dusty Creek and rested on the slope (Fig. 3.24).

The fact that some 1984 debris came to rest on the south-east side of the valley of Dusty Creek implies that the velocity of the debris flow was high after the flow

Figure 3.21 Mud Spatters, at Point 7, Fig. 2.4

Figure 3.22 Mud Spatters on Whole Upstream Side of Trees, Point 7 on Fig. 2.4

Figure 3.23 Airborne Wood Pieces, at Point 8 on Fig. 2.4

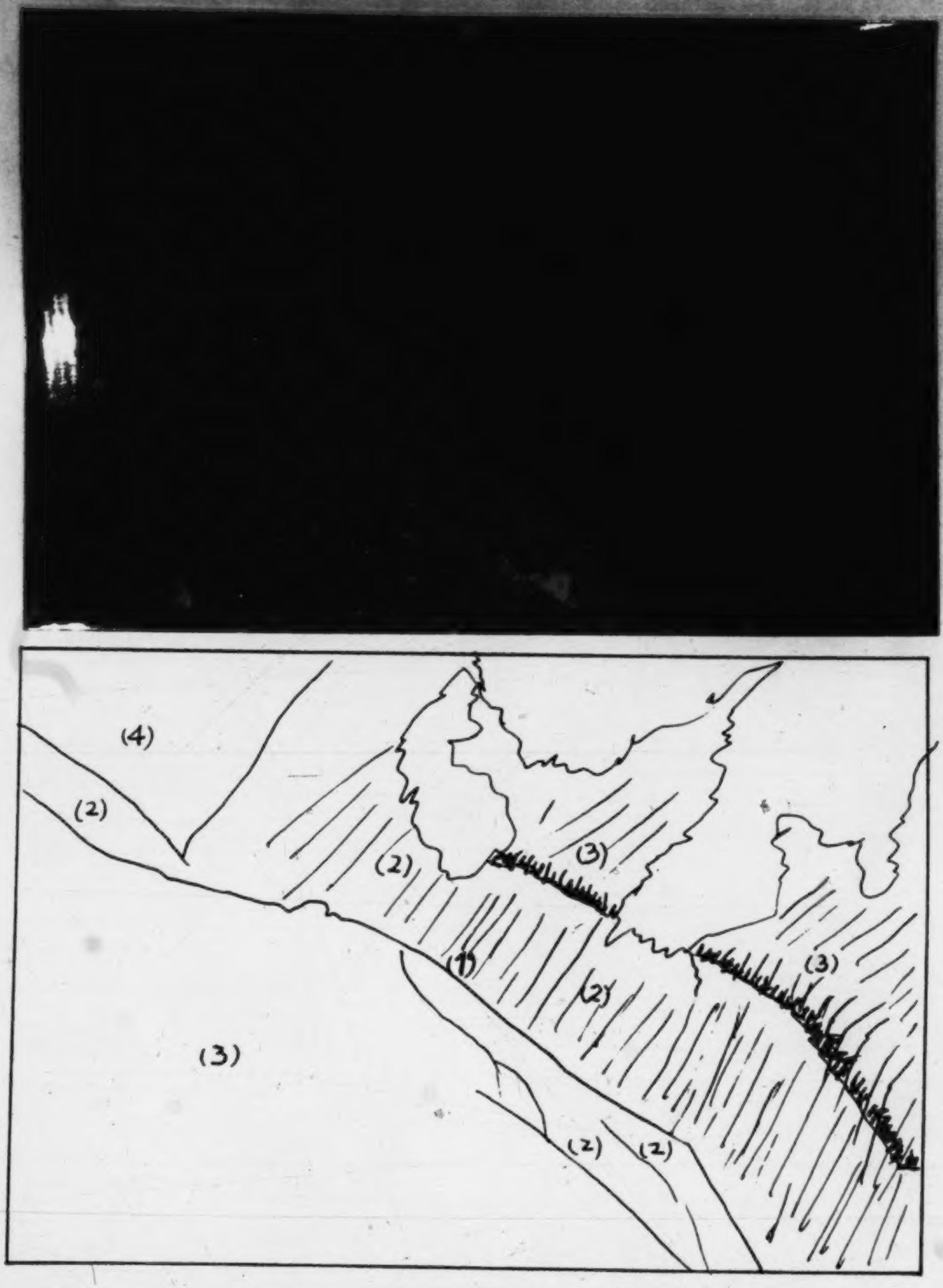

Figure 3.24 Debris Flow Deposits on Both Sides of Dusty Creek at Point 9 on Fig. 2.4

(1) Dusty Creek; (2) 1963 deposits; (3) 1984 debris flow deposits; (4) Basement rock.

passed over the ridge between Turbid and Dusty Creeks.

The horizontal distance between the distal point of debris deposit on the south-east side of Turbid Creek and the ridge is 100 m. The altitude difference between these two points is 6 m. And the highest deposits on the south-east side are 40 m above the stream bed of Dusty Creek. These measurements will be used to calculate the velocity of the mud and debris flow in section 3.6.

3.4.6 Damaged and Undamaged Vegetation

The 1963 rock avalanche deposits were covered by bushes up to 2.5 m high. As most of the 1963 deposits has been blanketed by the 1984 debris flow deposits, the bushes were buried. (Figs. 2.5 and 3.25). But the bushes on the top surface of block 3 of 1963 deposits escaped from the catastrophe (Fig. 2.9).

As the thickness of the 1984 debris flow deposits on the top of the escarpment is in the range, 0.5-2.0 m and generally less than 1 m , and the heights of the bushes are up to 2.5 m, it is reasonable to assume that the mud and debris flow was moving in waves with a high velocity and the bushes had been pushed down before they were buried.

The damaged vegetation indicates the 1984 debris flow path. As the bushes on block 3 of 1963 deposits survived the 1984 debris flow, the main path of the debris flow came down block 2 to its end, then it turned north-westwards and crossed the valley of Turbid Creek. As a result, the

Figure 3.25 Light Yellow Rock Belt, At Point 12 on Fig. 2.4

north-west part of block 2 (the small hill between Turbid and No Name Creeks) was blanketed by 1984 debris flow deposits, and the bushes on the top of block 3 escaped. After the debris flow reached the edge of the valley of Turbid Creek, it turned south-eastwards and crossed Turbid Creek again. So the bushes on block 1 were buried and some debris entered the valley of Dusty Creek.

3.4.7 Huge Boulders Deposited on the Top Surface

Fig. 3.14 shows a huge boulder on the 1984 debris flow deposits which covered the escarpment of the 1963 rock avalanche deposits at point 4. The huge boulder was carried on the surface of the debris flow and supported by fine particles and small blocks. The dimensions of the huge boulder are 3.2 m long by 1.6 m wide and 1.5 m high, giving a volume of 7.7 m^3 and a mass of approximately 15 t. Some fine particles stick on the surface of the boulder and blocks up to 0.3 m in size rest on the top of the boulder. The deposit beneath the boulder is just 2 m in thickness.

This boulder is an example of at least eight similar boulders on the top of 1984 deposits which cover block 1 of the 1963 deposits.

3.4.8 Light-Yellow Rock Belts

As shown in Fig. 3.25, a belt of small light-yellow breccia blocks is on the top of the debris flow. These small light-yellow breccia blocks were not mixed with other rock debris indicating that the debris flow was moving in a laminar flow, with materials in layers or belts whichrarely mixed.

3.5 Information from Eyewitnesses

Nobody witnessed the 1984 event in the upstream area, but at least eight people witnessed the movement of the debris flow downstream near the mouth of Turbid Creek. Six employees of Empire Logging were interviewed by the author. A detailed description of the phenomenon has been received from the hydrometic survey technician, Ruta O. Jaugelis. A newspaper report about the event has also been received from Jaugelis.

3.5.1 Newspaper Report

The Squamish Times (1984) reported, " About 4:30 on Thursday afternoon, after a few days of heavy rain, a wall of mud and debris came down the bed of Mud Creek, taking out the bridge which was at least 30 feet above the stream bed. .... Woods superintendent Pat O'Brennan said the mud came down in waves, blocking the Squamish River and then breaking loose, only to be followed by successive waves of mud, which again blocked the river. ...... These waves were still coming down early on Friday morning, O'Brennan said, a portion of the road was engulfed in the mud from the creek."

The following points need to be clarified.

The report appeared in the newspaper on July 10, 1984. The event was reported to be on Thursday. The Thursday is not the previous Thursday but, from the loggers and Jaugelis, the mud and debris flow they witnessed happened on June 28, 1984.

The report mentioned Mud Creek, the name the logging company and the loggers prefer to use. Mud Creek is the creek denoted by Turbid Creek on the published maps.

The road mentioned in the report is the logging road along the Squamish River. The bridge was on Turbid Creek near its mouth.

3.5.2 Information from Jaugelis

Jaugelis wrote (1987), " I witnessed the actual event on June 28 briefly from both sides (before and after the helicopter ride across the gap), for perhaps a half-hour to an hour. The magnitude of the event was awe-inspiring, in terms of the noise rumbling from the distance and the volume of mud and debris coming down in successive waves, large enough to flow above the road level as the picture shows (Fig. 3.26). I would say the picture was taken at not quite the peak of a typical wave. ... When I arrived a number of vehicles were parked, stranded on the north side of the creek. Shortly afterwards another wave of mud and debris came down. The rumble could be heard from a distance, and a tongue of mud could be seen flowing downstream from a distance as well. The momentum was enough that the flow crossed the Squamish River and travelled up the right bank against the rock face, then back down into the river. Enough mud and debris was carried down in successive waves to back up the Squamish River upstream for a distance."

Fig. 3.26 shows the debris flow moving on the logging road bridge.

3.5.3 Information from the Logging Company Employees

Three employees (Charlie Deminger, John Thompson and Peter Thomson) of Empire Logging have been interviewed. They have emphasized that there were a lot of ice blocks accumulated in the stream bed of the creek near the logging road.

From this information, some major points about the debris flow emerge:

1. The mud and debris flow happened on June 28, 1984.
2. The flow was moving in waves.
3. The mud and debris flow crossed the Squamish River and travelled up the right bank.
4. The Squamish River was blocked by the mud and debris flow.
5. The major event lasted at least 2 hours (at 4:30 PM a wall of mud and debris came down, Jaugejis arrived about 6:00 PM and watched for perhaps a half-hour to an hour).

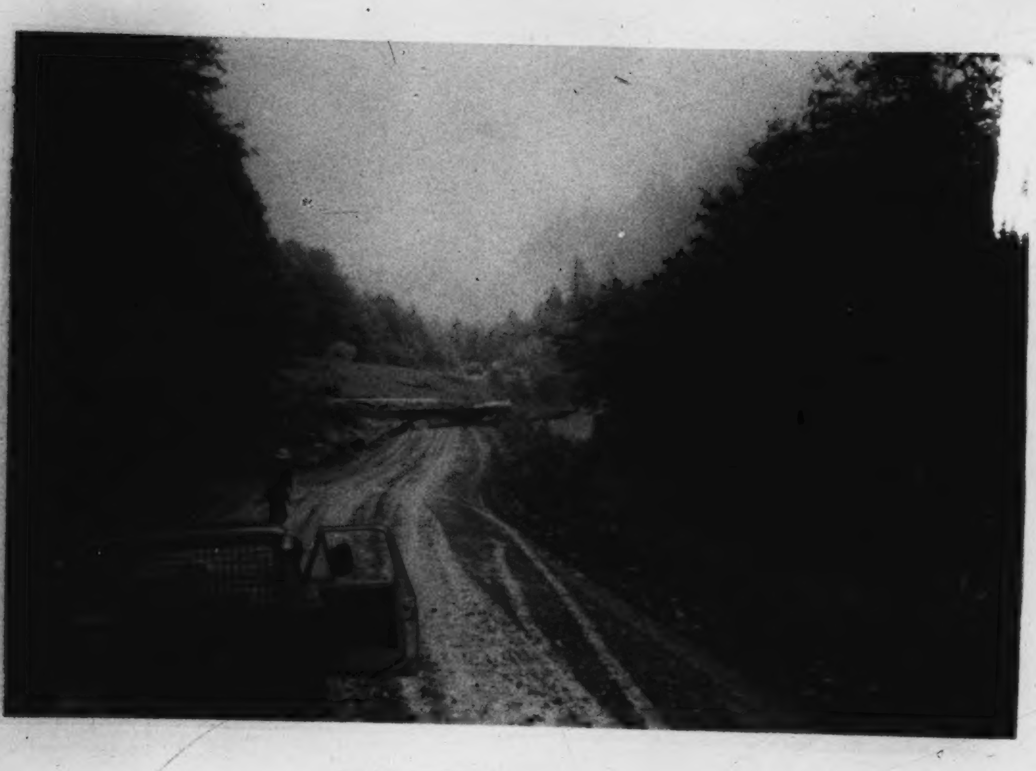

Figure 3.26 Debris Flow Moving on the Bridge (Photo by Jaugelis)

3.6 Interpretation

The general movement path of the debris, the mechanism of the debris flow and the special characteristics of the debris flow have been inferred from the characteristics of the deposits and the special phenomena created by the rock avalanche and the debris flow.

As the deposits show two different types, two stages of the 1984 event can be inferred, a rock avalanche stage and a debris flow stage.

3.6.1 Rock Avalanche Stage

A huge rock mass (200x300x150 m) detached from the scarp and slid towards the opposite (south) bank. Then the rock mass broke up and travelled downstream along the creek valley. The debris came to rest around the confluence of Avalanche and Turbid Creeks. The creeks were dammed.

A remnant of the debris dam has been found (Fig. 3.5) 50 m upstream from the confluence with Turbid Creek. The debris travelled over the water-dividing ridge between Avalanche and Turbid Creeks, rushed into Turbid Creek upstream of the confluence and dammed Turbid Creek. The base of the remnant of the debris dam is at 904 m and its top is at 910 m in the stream. The top of the remnant of the debris dam on the north-west bank of Turbid Creek is at 930 , at which point the debris deposits are 20 m thick. The width of the debris dam on the north-west bank is 30 m. The remnant of the debris dam in the stream and on the both sides consists of light yellow breccia and purple lapilli, which came from Unit 5 of the volcanic rock in the source area.

From the confluence to 300 m downstream, typical rock avalanche deposits are on the south-east side of the valley. So the rock avalanche debris travelled 1.6 km downstream to the confluence of Avalanche and Turbid Creeks.

3.6.2 Debris Flow Stage

Avalanche and Turbid Creeks were dammed. Water was continuously accumulated behind the dam from two different sources, ice melted by the friction with the travelling debris and the valley wall and the water flowing down the two creeks, especially from Turbid Creek.

It is reasonable to assume that there were ice blocks in the creek in late June 1984. Two facts strongly support that ~~assumpt~~ion. First, the employees of Empire Logging saw ice blocks accumulated in the stream bed of Turbid Creek around the logging road on June 28, 1984. The ice blocks were carried by the debris flow and came to rest there. Secondly, there was lots of ice in the source area and the valley of Avalanche Creek on August 19, 1986 when I collected tuff samples there. Presumably, ice was dug out from the bottom of the creek by the rock avalanche and carried downstream. As the debris was travelling at a high velocity, heat was released by the friction between the valley walls and the travelling debris. Ice blocks were melted during the debris movement. Water also came from the flow of Turbid Creek, after two days of heavy rain (50 mm) (Jordan 1987). So, water accumulated behind the debris dam.

The water pressure increased while the water accumulated continuously. When the dam was breached, water carried mud and debris downstream rapidly. Debris flow deposits and a series of special phenomena are seen downstream from the debris dam.

3.6.3 Path of the Debris Flow

The path of the debris flow is shown on Fig. 3.27 from the indications of the debris flow deposits and the damaged and undamaged vegetation. The debris flow formed around the confluence of Avalanche and Turbid Creeks. Then it moved towards the south bank of Turbid Creek, where the debris flow impacted the creek wall, at point 30, and turned to the north side and crossed the creek. When the debris flow impacted the north wall of the creek at point 25, it changed direction towards the south side and crossed the creek. At point 24, the debris flow was divided by a small ridge. The main branch moved along the creek bed, but a small branch moved along a gully near the south wall of the creek. The top of the ridge was untouched by the debris flow, no depcsits rest there and the vegetation is preserved(Fig. 3.28). After passing the ridge, the debris flow moved along the creek valley towards its south side. At the former confluence of Dusty and Turbid Creeks (point 10), the

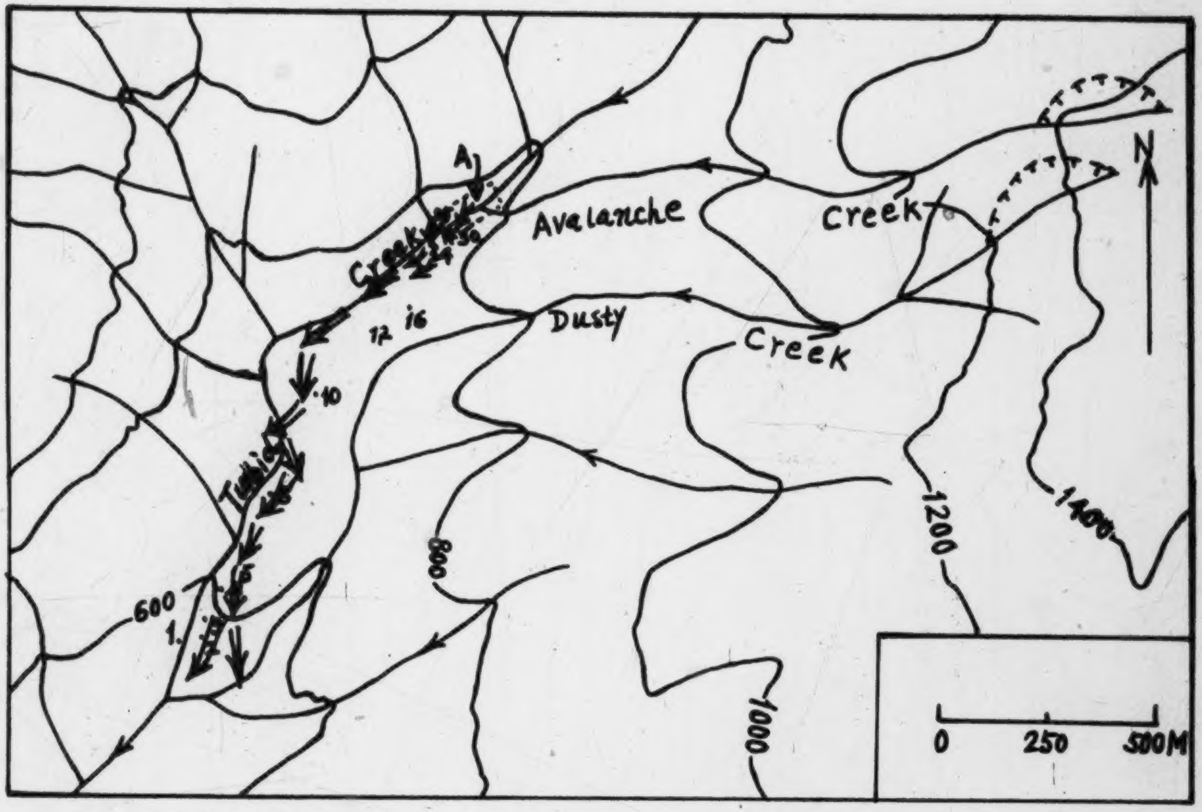
N
A
Avalanche
Creek
Creek
Dusty
Creek
30
24
16
12
10
6
1
600
800
1000
1200
1400
0
250
500M

Figure 3.27 General Path of Debris Flow

1,2,6...Points 1,2,6...; A-Location of Fig. 2.28 ↙ Debris movement direction

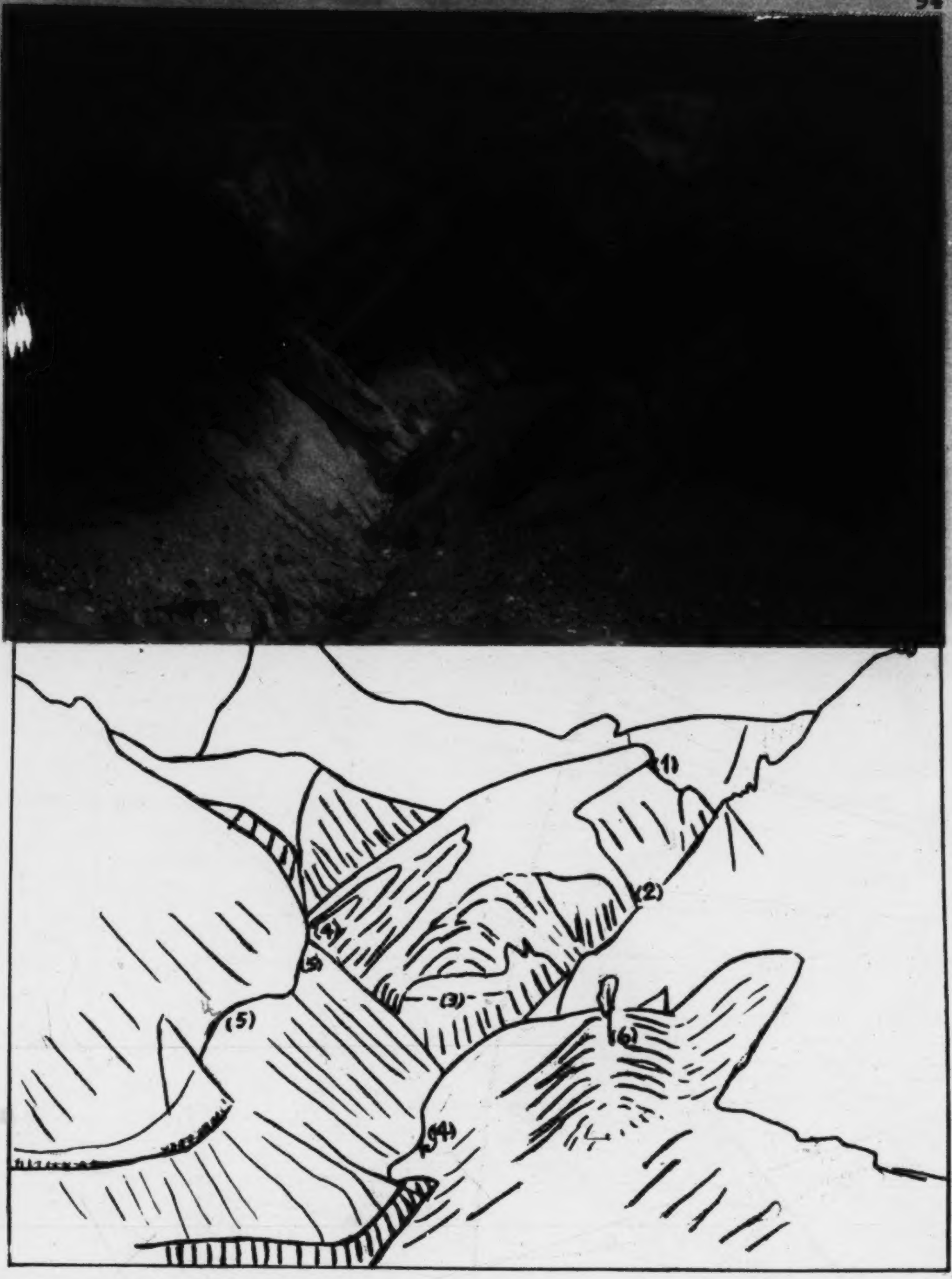

Figure 3.28 Untouched Ridge, Location Shown as A on Fig. 3.27

(1) Source area of 1984 rock avalanche; (2) Avalanche Creek; (3) 1984 deposit mark; (4) Turbid Creek; (5) Superelevation mark; (6) Untouched ridge.

debris flow turned towards the north side of the creek. When it impacted on the steep walls at the north side of Turbid Creek it turned back towards the south side again, the debris oscillated. So it created two special phenomena: first, the bushes on the main part of block 3 of the 1963 rock avalanche deposits escaped from the disaster, and secondly a superelevation on the north side of the creek. After this bend, the debris flow moved along the south side of the creek valley to cover the downstream part of block 3 and the whole block 1 of the 1963 rock avalanche deposits with 1984 debris flow deposits and bury the bushes. At the downstream of block 1 (point 4), the debris flow travelled over the top of the escarpment and rushed into Dusty Creek. Part of the debris flow was airborne so that some deposits occur on the south side of Dusty Creek.

After passing block 1, the debris flow was confined to the creek valley till entering the Squamish River.

3.6.4 Secondary Temporary Dam

The deposits of the debris flow are generally 0.5-2.0 m thick and reached 30-40 m above the stream bed. These deposits covered the stream bed, the slopes and the top surface of the escarpment to a similar depth, 0.5-2.0 m (Figs. 3.7, 8, 9, 10 and 11). So it is reasonable to assume that the debris flow reached about 2-3 m above the top surface of the escarpment and the valley of the creek was filled by debris. But later on, most of the materials were carried away downstream. As a result, only a layer, 0.5-2.0 m thick was left on the flatter spots.

The debris flow was triggered by the burst of a debris dam caused by the rock avalanche. But when the debris flow travelled downstream, the creek was blocked at several spots by the debris because the valley was so narrow and the flow was so viscous. Following debris was stopped by the blockages and the debris accumulated behind and over the secondary temporary dam until the dam reached about 2-3 m higher than the top surface of the escarpment. At that time, the whole valley was filled with debris, and following debris was oscillating in the debris-filled valley.
The secondary temporary dam was located at the end of block 1 of the 1963 rock avalanche deposits near point 1.

When the weight of the accumulated debris and the following debris exceeded the strength of the debris, the dam was broken. A new debris flow travelled downstream. Most debris was carried away by the following debris flows from upstream. The deposits on the stream bed sides might be the remainder of the valley-fill debris or the new debris.

The damming and breaking processes repeated several times, each lasting for about 30 minutes, as the debris flow waves were observed for about 2 hours or more near the mouth of Turbid Creek.

3.6.5 Windblast

Uprooted trees and airborne wood pieces were created by strong wind or windblast. near the end of the secondary temporary dam (points 1, 2, 3, 4 and 5). Presumably the air was strongly compressed by the quickly moving mud and debris flow. Then strong winds formed and uprooted trees, spattered mud on trees up to 16 m above the ground and blew wood pieces and rock blocks into trees.

3.6.6 Rock Blocks Hurled Through Air

It is evident that the debris deposits on the south side of Dusty Creek valley were hurled through the air, because no continuous 1984 deposits have been found in Dusty Creek valley and these deposits are distinctive light yellow breccias. This indicates the high velocity of the debris flow and results in windblast.

3.7 Velocity Evaluation

The velocities of rock avalanche debris, and the debris flow can be estimated from the special phenomena.

Huge boulders on the top of the debris flow indicate that the debris flow was viscous and with a high velocity.

Airborne wood pieces are small and light, so the wind that brought them should be strong enough to drive these wood pieces into the trunk. In addition, the velocity of the debris flow should be high enough to compress the air to create the strong wind, which caused the trees uprooted.

Rock blocks hurled through the air from the 1984 debris rest on the south bank of Dusty Creek. Certainly, this phenomenon would help to evaluate the velocity of the debris flow.

Superelevation has been found at two sites. One, at the confluence of Avalanche and Turbid Creeks represents the superelevation of the rock avalanche debris, the other at the former confluence of Dusty and Turbid Creeks represents the superelevation of the debris flow.

3.7.1 Velocity Evaluation from Superelevation

As mentioned above, superelevation site 1 at the confluence of Avalanche and Turbid Creeks can be used to calculate the velocity of the rock avalanche.

Superelevation site 2 at the former confluence of Dusty and Turbid Creeks created by the debris flow can be used to calculate the velocity of the debris flow.

Johnson and Hampton (1969) have derived a quantitative relation between the mean velocity, V , of a debris flow, tilt, P , of the flow surface at a bend and the radius of the curvature of the bend, R , as

$$V = (RgtanP)^{0.5} \qquad (3.1)$$

Where g is the acceleration of gravity

For the 1984 rock avalanche debris at superelevation site 1, R=400 m, and tanP=0.2669, so V=32 m/s.

For the debris flow at superelevation site 2, R=700 m,, and tanP=0.15, so V=32 m/s.

3.7.2 Velocity Evaluation from Debris Hurled Through Air

As data on projectile size and shape, launch and impact angles, and air density along the flight path are not known, the debris on the south bank of Dusty Creek could not be used for accurate velocity calculation. However, as the debris rest 40 m above the stream bed of Dusty Creek, assuming that all the kinetic energy was converted to potential energy, the relation

$$V=(2gh)^{0.5} \qquad (3.2)$$

Where h is the height at where the debris comes to rest and

V is the velocity of debris flow.

gives for h=40 m, so V=28 m/s.

3.7.3 Velocity Estimation from Uprooted Trees

As mentioned previously, the uprooted trees imply that there was a very strong wind which created by the debris flow. According to the Beaufort Scale of Winds, trees would be uprooted by the wind of Beaufort number 10. Its velocity above ground should be 88.5-101.4 km/hour (Strahler, 1975, p.147), equivalent to 24.628.2 m/s. As we know that the wind velocity should not be higher than the debris flow which caused the wind, it is concluted that the velocities of the debris flow calculated from the superelevation and evaluated from the debris hurled through air are very well matched by this estimat.

3.7.4 Discussion

From the calculations above, the velocity of the 1984 rock avalanche debris is 32 m/s, the velocity of the debris flow is 28-32 m/s. Compared with the mean velocity of the 1963 rock avalanche, 16m/s (Clague and Souther 1982) the velocity of the 1984 rock avalanche debris is much higher. It is clear that the tilt of the flow surface of the 1984 event (tan15°) was much larger than that of the 1963 event, (tan3.5°), giving a much higher superelevation.

3.8 Damage to the Logging Road and Influence on the Squamish River

The 1984 event did not cause any loss of life, but the rock avalanche and the debris flow did cause damage to the logging road and influence the Squamish River.

From the newspaper report and the letter from Jaugelis, the damage on the logging road caused by 1984 event was loss of the bridge on the logging road and a portion of logging road (0.5 km) was engulfed in the mud from the creek.

The road on the left bank of the Squamish River was washed out for 3 kilometres, as a result of the Squamish River baking up at Turbid Creek and then releasing, and possibly due to the kind of debris being carried.

Huge quantities of mud and debris were brought into the Squamish River by the 1984 event. As a result of these rock avalanches and debris flows, the Squamish River is fully filled with debris. The 1984 event caused significant channel change in this part of the river, so the Squamish River has been seriously barricaded by the deposits of mud and debris (Fig. 3.29). If a large rock avalanche took place on Mount Cayley while the river is fully filled with water, debris flows may occur in the Squamish River. They may cause serious damage to the communities along the river, even the town of Squamish.

3.9 Summary

The main conclusions about the 1984 event on Mount Cayley are as following.

The 1984 event on Mount Cayley includes two stages, rock avalanche, and debris flow.

In the first stage, a mass of light yellow breccia, purple lapilli and jointed dacite 200 m in length, 300 m in width and up to 150 m in depth detatched from the scarp. The mass slid south, picked up ice blocks from the creek valley, impacted the south-east wall of the valley and broke up. Then the rock avalanche debris travelled downstream, largely confined to the valley of the creek. The rock avalanche debris overtopped the small ridge between Avalanche and Turbid Creeks, and came to rest around the confluence and dammed these two creeks.

In the second stage, the water coming from the upstream of Turbid Creek and the melted ice blocks accumulated continuously behind the dam, the debris dam burst, and a debris flow formed, moving with a high velocity.

Figure 3.29 Highly Alluviated Squamish River

These two stages created different deposits. The rock avalanche directly influenced only 1.6 km of the valley from the source area to 300 m downstream from the confluence of Avalanche and Turbid Creeks. The debris flow influenced about 4.6 km, from the confluence of Avalanche and Turbid Creeks to the Squamish River. Typical rock avalanche deposits occur around the confluence and typical debris flow deposits along Turbid Creek down to the mouth of the creek.

The rock avalanche deposits, 20-40 m thick, consist of huge boulders and blocks of light-yellow breccia and purple lapilli. The debris flow deposits are generally 0.5-2.0 m thick, the maximum thickness is 6 m, and consist of small blocks and particles of light-yellow breccia and purple lapilli with very few boulders.

Some secondary temporary debris dams were formed by the viscous debris flow. As the debris from the following debris flow accumulated, the top of the debris dam reached 2-3 m above the top of the escarpment, about 45 m above the stream bed. So the debris flow left 0.5-2.0 m thick deposits on the top of the escarpment. Even though the valley was filled with mud and debris, the accumulation of debris and the push from successive debris flow burst these secondary temporary dams one after another. The breaching carried debris downstream, and created secondary debris flows moving in waves which were witnessed from the logging road.

As most of debris accumulated in the valley was carried downstream, 0.5-2.0 m thick deposits were left on the gentle slopes and the stream bed.

The local velocity of the rock avalanche was 32 m/s. The velocity of the debris flow was 28-32 m/s.

As the velocity was high, special phenomena were observed: high superelevations, uprooted trees, high mud spatters, and wood pieces and rock blocks hurled through air.

4. GEOTECHNICAL PROPERTIES OF VOLCANIC TUFF

4.1 Introduction

The volcanic tuff examined in this research is thought to constitute the basal rupture zone of the 1984 rock avalanche on Mount Cayley, and be one of the most important factors in the formation of the viscous debris flow. To understand the behavior of volcanic tuff and the mechanism of landslides on Mount Cayley, a laboratory programme was carried out on volcanic tuff collected in the Summer 1986 from the head scarp area of 1984 rock avalanche. Sampling location is indicated in Figure 3-2. As most of tuff layers outcrop on very steep slopes which are inaccessible, four block samples were collected from the lower part (white-grey tuff) of Unit 5 of the volcanic rock on Mount Cayley. As there was little exposure on the head scarp of the 1984 rock avalanche, these samples were collected from the same layer but at different elevation (1480-1482 m).

These samples are grey-white fine tuff. Lithic fragments up to 4 mm in length make up the grain component. The matrix is submicroscopic. The matrix is surprisingly resistant to the point of a steel needle and the lithic fragments could not be pried from the matrix with ease.

The particle size distribution was determined from the disintegrated specimens after slake durability testing (Fig. 4.1).

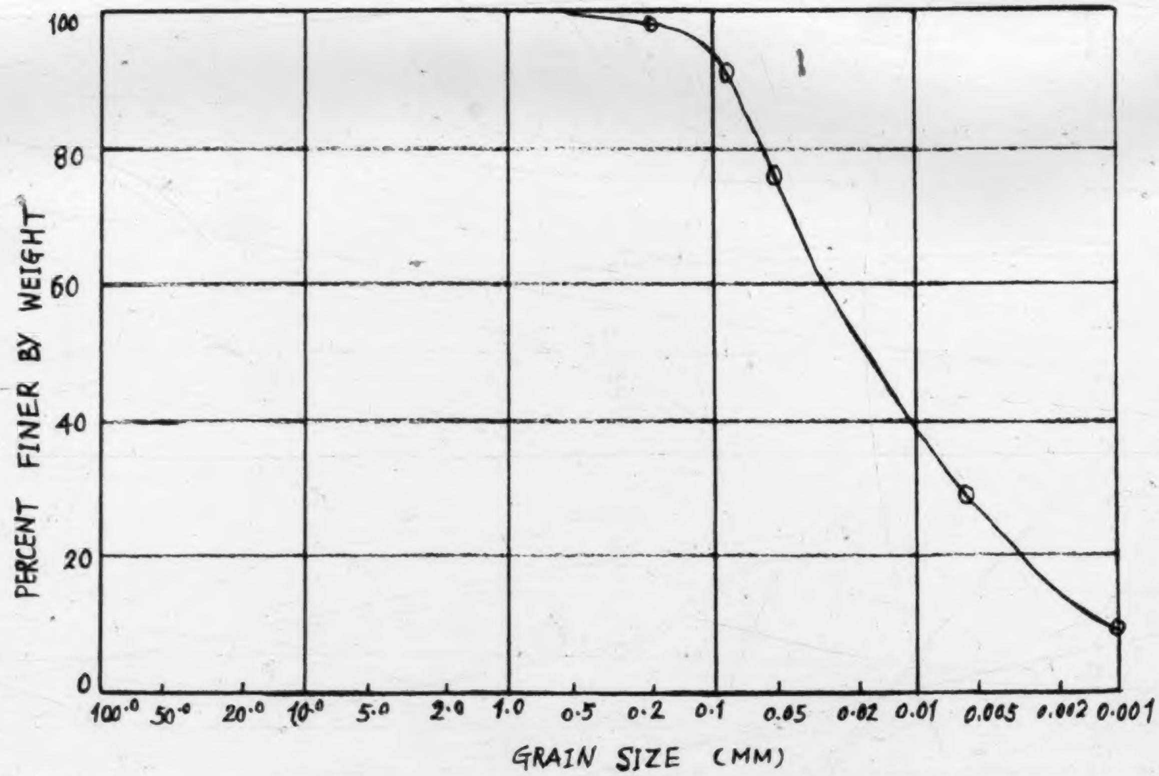

Figure 4.1 Particle Size Distribution

The testing specimens were prepared in the following order.

1. Columnar specimens first. The diameters of these specimens are almost the same (3.83-3.90 cm),but the lengths vary from 5.98 to 9.38 cm. Compressional wave velocity and dry porosity were measured from these specimens. They are now preserved for triaxial testing for further research.

2. Direct shear test and free swelling test specimens second. The diameters of these specimens are the same, 5.1 cm, the heights vary from 1.27 to 2.56 cm accordingly. Before direct shear and free swelling testing, the specimens were used for tilting table testing.

3. Finally, the remainders of the four block samples were prepared for dry bulk density determination, point load testing, water absorption testing and slake durability testing.

The geotechnical behavior of these tuff samples was characterised by engineering classification tests, estimates of the uniaxial compressive strength of the intact rock material, q_u together with the ultimate shear strength of artificially prepared surfaces. The objective of the laboratory programme was to investigate the relationship between the geotechnical behavior of volcanic tuff and the rock avalanche and debris flow.

The laboratory work carried out is summarised in Table 4.1.

Table 4.1 Summary of Laboratory Work

No	Type of Test	Material	Number of specimens
1	Elastic Wave Velocity	Tuff	9
2	Dry Density	Tuff	12
3	Wet Porosity	Tuff	15
4	Dry Porosity	Tuff	9
5	Slake Durability	Tuff	4
6	Point Load	Tuff	20
7	Free Swelling	Tuff	4
8	Direct Shear	Tuff	4
9	Tilting Table	Tuff	8

The laboratory programme was carried out under several constraints which resulted from the difficulties of sample collection and the character of the volcanic tuff. First, most of volcanic tuff layers outcrop on very steep slopes which are inaccessible. So available samples are limited. Second, the volcanic tuff was friable due to surface weathering processes or alteration, and it was difficult to collect block samples that did not exhibit cracking. This aspect of the intact material involved considerable waste in specimen preparation and limited the range of tests that could be carried out.

4.2 Dry Bulk Density And Porosity

4.2.1 Homogeneity and Isotropy

First, the specimens were checked for homogeneity and isotropy by measuring the compressional wave velocity in orthogonal directions. The results are listed in Table 4.2. No significant differences were found for any of the specimens investigated.

4.2.2 Dry Bulk Density

The dry bulk density, r_d , was established by the water displacement method outlined in Gyenge (1977) and ISRM (1979). In this method a fragment of tuff is oven-dried, weighed, coated with wax, weighed again and immersed in a measuring cylinder. The volume of water displaced is

Table 4.2 Results of Compressional Wave Velocity Measurements

No	L(cm)	Ts(10^{6}s)	Tp(10^{6}s)	Vp(10^{3}m/s)	E(MPa)
1-1	8.94	107	69	1.29	237
1-2	8.92	101	66	1.35	252
1-3	7.82	94	58	1.35	228
1-4	7.42	93	55	1.35	246
2-1	8.73	98	62	1.41	271
2-2	8.69	91	62	1.38	274
3-1	9.37	115	70	1.34	214
3-2	7.06	89	50	1.41	213
3-3	5.98	82	32	1.25	206

measured and corrected for the volume of wax coating and r_d is calculated by dividing the oven-dry weight by the corrected volume of water displaced.

The results are given in Table 4.3.

4.2.3 Porosity

Porosity was measured by two different methods.

1. Water absorption method

At first, the volume of tuff specimen was determined by the same method for establishment of dry bulk density. Then the wax removed specimen was immersed in distilled water for a period of one hour and 48 hours respectively. The specimen was removed and surface dried using a moist cloth, care being taken to remove only surface water and to ensure that no fragments are lost. Its saturated-surface-dry weights Wsat1 and Wsat48 were measured. So the alteration index (1 hour absorption) and 48 hour absorption porosity were determined (ISRM 1979). These results are listed in Table 4.4.

2. Dry porosity determination

The porosity of dry specimens was determined using the apparatus shown diagrammatically in Fig. 4.2 following Morgenstern and Phukan (1968). The specimen, of total volume V, was connected to a mercury manometer. Initially, the pressures in the void space (Vs) of the specimen and

Table 4.3 Results of Dry Bulk Density Measurements

No	W (g)	V (cm^3)	r_d (g/cm^3)
1-1	68.02	49.64	1.37
1-2	59.05	41.70	1.42
1-3	20.17	14.56	1.38
1-4	22.54	16.09	1.40
2-1	57.50	39.62	1.45
2-2	71.72	48.68	1.47
2-3	67.50	46.23	1.46
2-4	39.94	28.13	1.42
3-1	38.59	28.44	1.36
3-2	28.69	21.35	1.34
3-3	21.89	16.03	1.37
3-4	20.84	16.28	1.28
Mean			1.39
S.D.			0.05

Table 4.4 1 Hour and 48 Hours Absorptions

No	Wd(g)	V(cm^3)	W1(g)	W48(g)	P1(%)	P48(%)
1-1	52.89	37.78	63.17	64.20	27.2	29.9
1-2	60.47	42.90	72.26	73.43	27.5	30.2
1-3	23.82	17.01	28.67	29.20	28.5	31.6
1-4	122.55	80.62	145.25	147.44	28.2	30.9
1-5	98.49	66.71	117.26	118.90	28.1	30.6
2-1	44.48	32.00	51.97	53.22	23.4	27.3
2-2	77.89	50.17	89.34	91.49	22.8	27.1
2-3	72.25	60.91	85.73	86.67	22.1	23.7
2-4	75.71	57.54	87.05	89.00	19.7	23.1
2-5	75.31	41.39	83.88	85.03	20.7	23.5
3-1	30.50	21.94	37.40	37.82	31.4	33.4
3-2	17.32	12.37	20.80	21.21	28.1	31.4
3-3	71.29	49.32	87.12	88.67	32.1	35.2
3-4	101.06	67.21	120.69	122.43	29.2	31.8
3-5	118.24	72.96	142.83	144.62	33.7	36.2
Mean					26.8	29.7
S.D.					4.1	3.9

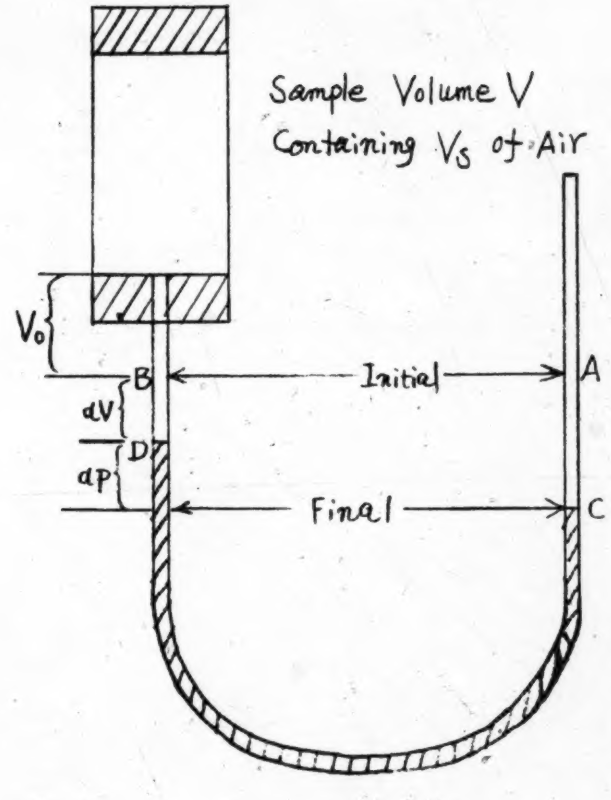
Sample Volume V
Containing V_s of Air
V_0
B
A
Initial
dV
D
dP
Final
C

Figure 4.2 Apparatus for Dry Porosity Determination

in the void space (Vo) over the left-hand side of manometer were both atmospheric. The left and right hand limbs of the manometer were at B and A respectively. The specimen was then surrounded by a rubber membrane and sealed between top and bottom caps with O rings so that no air could flow into the specimen. The right hand limb of the manometer was lowered to C. The left hand limb droped to D so that there was a pressure decrease in the closed off pore space with an associated volume increase both which were readily measured. From Boyle's Law the volume of void space in the specimen is

$$Vs=Pa \times dV/dP-Vo-dV \qquad (4.1)$$

where

Vs is the volume of air in the specimen,

Vo is the initial volume of air between the specimen and manometer,

dV is the change in volume of air due to the decrease in pressure P,

Pa denotes atmospheric pressure, and

dP is the decrease in pressure in the sealed void space.

In the determinations of this study, dP was usually equal to Pa/2 and then Vs is given by

$$Vs=dV-Vo \qquad (4.2)$$

The results from this method are listed in Table 4.5.

A comparison of the porosities given by the two methods is shown in Fig. 4.3.

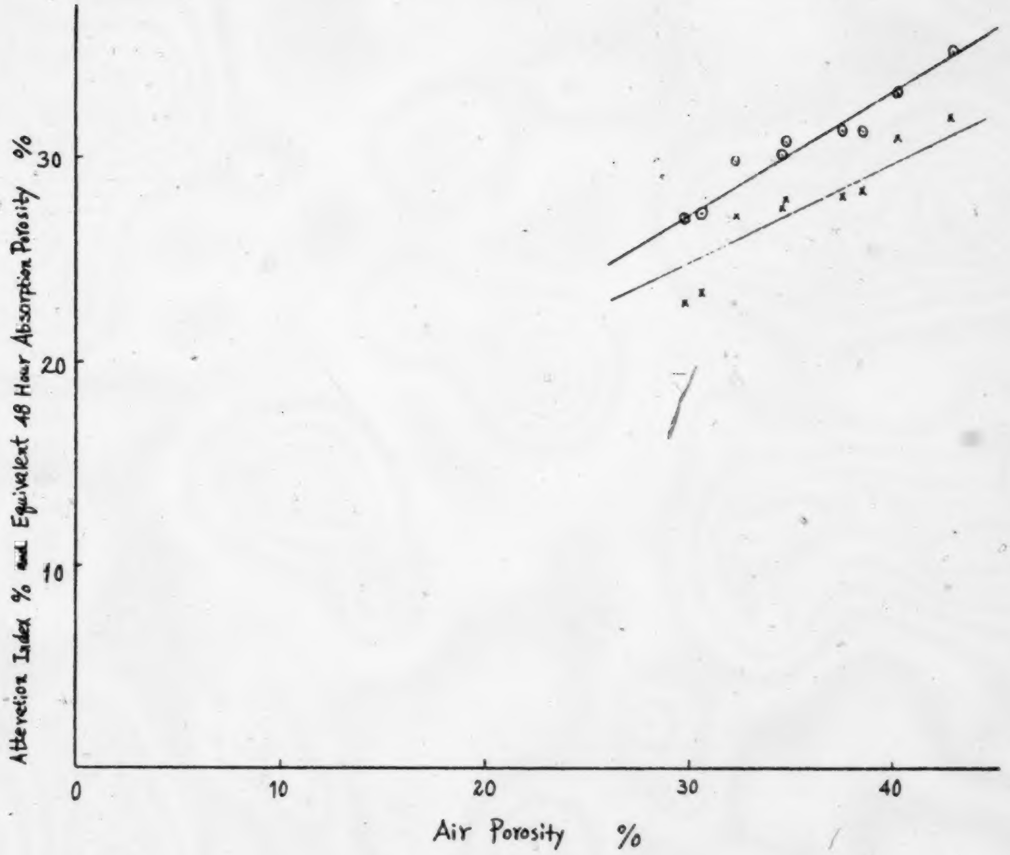

Figure 4.3 Comparison of Dry Porosity with Absorptions X 1 Hour absorption/dry porosity; ⊙ 48 Hour absorption/dry porosity

4.3 Slake Durability

The water deterioration characteristics of 4 intact specimens were established using the Slake Durability Test. As estimation of the water deterioration characteristics of the material is important in estimating the role for long term strength changes (softening) and changes of slope stability with time (Morgenstern and Eigenbrod, 1974). The standard apparatus and method, recommended by Franklin and Chandra (1972) and ISRM (1979) were used. In this test, ten lumps of material weighing approximately 500 g were subjected to two cycles of 6 hours drying and 10 minutes of tumbling and wetting. Distilled water was used in the test. The Slake Durability Index (SDI) is the ratio of the oven-dry weight of rock remaining in the drum after the 2 cycles of slaking to the initial oven-dry weight expressed as a percentage.

The Slake Durability Test is a measure of the ease with which water can enter the rock, the reaction of the fabric to the ingress of water (e.g., solution of cement, hydration, destruction of interparticle bonds) and the resistance of the rock material to this reaction in the form of intergranular strength (i.e. water sensitive cohesion). The test results are seen in Table 4.6. The indexes are very low.

Table 4.5 Dry Porosity and Comparison with Absorption Indexes

No	P1 (%)	P48 (%)	Pd (%)
1-1	27.2	29.9	32.35
1-2	27.5	30.2	34.69
1-3	28.5	31.6	38.19
1-4	28.2	30.9	34.88
2-1	23.4	27.3	30.56
2-2	22.8	27.1	29.98
3-1	31.4	33.4	40.27
3-2	32.1	35.2	43.11
3-3	28.1	31.4	37.79
Mean	27.7	30.8	35.76
S.D.	2.9	2.5	4.19

Table 4.6 Slake Durability Index

No	Wa (g)	Wb (g)	Wc (g)	Wd (g)	SDI 1 (%)	SDI (%)
1-1	2424	2113	2043	1908	39.7	26.2
2-1	2418	2108	2046	1908	39.2	27.0
3-1	2410	2119	2036	1908	42.0	25.5
3-2	2448	2130	2044	1908	41.1	25.2
Mean					40.5	26.0
S.D.					1.11	0.7

4.4 Point Load Strength And Estimated Uniaxial Compressive Strength (q_u)

Point load test was conducted on the volcanic tuff collected from Mount Cayley. Details of the test may be found in Broch and Franklin (1972) and Bieniawski (1974). As discussed by these authors, an approximation to the uniaxial compressive strength (q_u) may be obtained by the test.

Irregular lumps of rock were obtained from large blocks which had been air dried. Irregular lump tests were then carried out according to the procedures followed by Broch and Franklin (1972).

The lumps were placed between the conical platens of the point load apparatus and the separation of the platens (D) measured. The platens were then driven toward each other by hydraulic jack and the load at which the rock lump failed (P) was measured on a dial gauge.

To obtain the Point Load Strength of the rock (Is), following Broch and Franklin (1972)

$$Is=P/D^2 \qquad (4.3)$$

The Point Load Strenhth Index of the rock is the median value of Is and the results are presented in Table 4.7. An approximation to the unconfined compressive strength (q_u) of the rock may be obtained by

$$q_u=24Is \qquad (4.4)$$

Values of q_u obtained by Equation 4.4 are shown in Table 6.7. Values of q_u varied between 4.8 MPa and 5.8 MPa.

Under the Geomechanics Classification Scheme of Bieniawaski (1979) they are considered to be very low strength (1-5 MPa) or low strength (5-25 MPa).

For comparison, an uniaxial compressive testing was carried out on one dry and one saturated columnar specimens. The uniaxial compressive strength of the dry specimen was 5.1 MPa and the saturated specimen was 3.3 MPa respectively. The saturated specimen collapsed rapidly when it failed.

4.5 Free-Swelling Pressure

The volcanic tuff on Mount Cayley, notably with high clay content, is prone to swelling, weakening or disintegration when exposed to short term weathering processes of a wetting and drying nature. Special tests are necessary to predict this aspect of mechanical performance.

The ability of tuff to swell when water is introduced to it was estimated by free swelling pressure measurement, measurement of swelling pressure when the specimen is confined radially and is subjected to a known axial stress. So an oedometer was used to prevent volume change. Free swelling pressure was determined by the axial strength.

Free swelling pressures of 6 tuff specimens range from 2-5 KPa.

Table 4.7 Point Load Strength Index

No	D	P	Is (MPa)	q_u (MPa)
1-1	0.79	20	o.221	5.31
1-2	0.99	32	0.225	5.41
1-3	0.87	23	0.210	5.03
1-4	0.82	22	0.226	5.42
1-5	0.75	18	0.221	5.30
1-6	0.88	25	0.223	5.35
1-7	0.89	26	0.226	5.43
2-1	0.85	25	0.239	5.73
2-2	0.86	26	0.243	5.82
2-3	0.85	24	0.229	5.50
2-4	0.79	21	0.232	5.57
2-5	0.83	24	0.240	5.77
2-6	0.80	22	0.237	5.69
3-1	0.87	22	0.201	4.81
3-2	0.92	27	0.220	5.28
3-3	0.85	23	0.220	5.28
3-4	0.83	22	0.220	5.28
3-5	0.79	20	0.221	5.31
3-6	0.94	26	0.203	4.87
3-7	0.94	28	0.219	5.25
Mean			0.224	5.37
S.D.			0.011	0.26

4.6 Direct Shear Tests

Direct shear tests were carried out on the tuff samples collected from Mount Cayley.

Four pairs of tuff specimens were tested in a D=5.1 cm high capacity shear box. Specimens were cut by saw and sanded to fit the box. Prior to placement an artificial shear surface was prepared by saw cut. The key point is to arrange the pre-cut surface to coincide with the real shear surface in testing.

Several difficulties were encountered in specimen preparation and testing. In cutting the specimens to fit the shear box, much of the rock fractured, making it impossible to prepare a large number of specimens. In the testing process, specimens in the shear box were frequently ruined by degradation around the edges during the movement of the shear box, especially when the specimens were wet. To avoid excessive cracking around the edges of the specimens, the travel distance of shear box was restricted.

Direct shear testing was carried out on dry specimens first. Then the shear box was flooded for 48 hours with distilled water, and the specimens were sheared again. In all of the tests on saturated tuff, a thin slickensided film of clay developed on the shear surfaces. This film probably accounts for the drop of the friction angle.

The shear strength envelopes are presented in Figs 4.4, 4.5, 4.6 and 4.7.

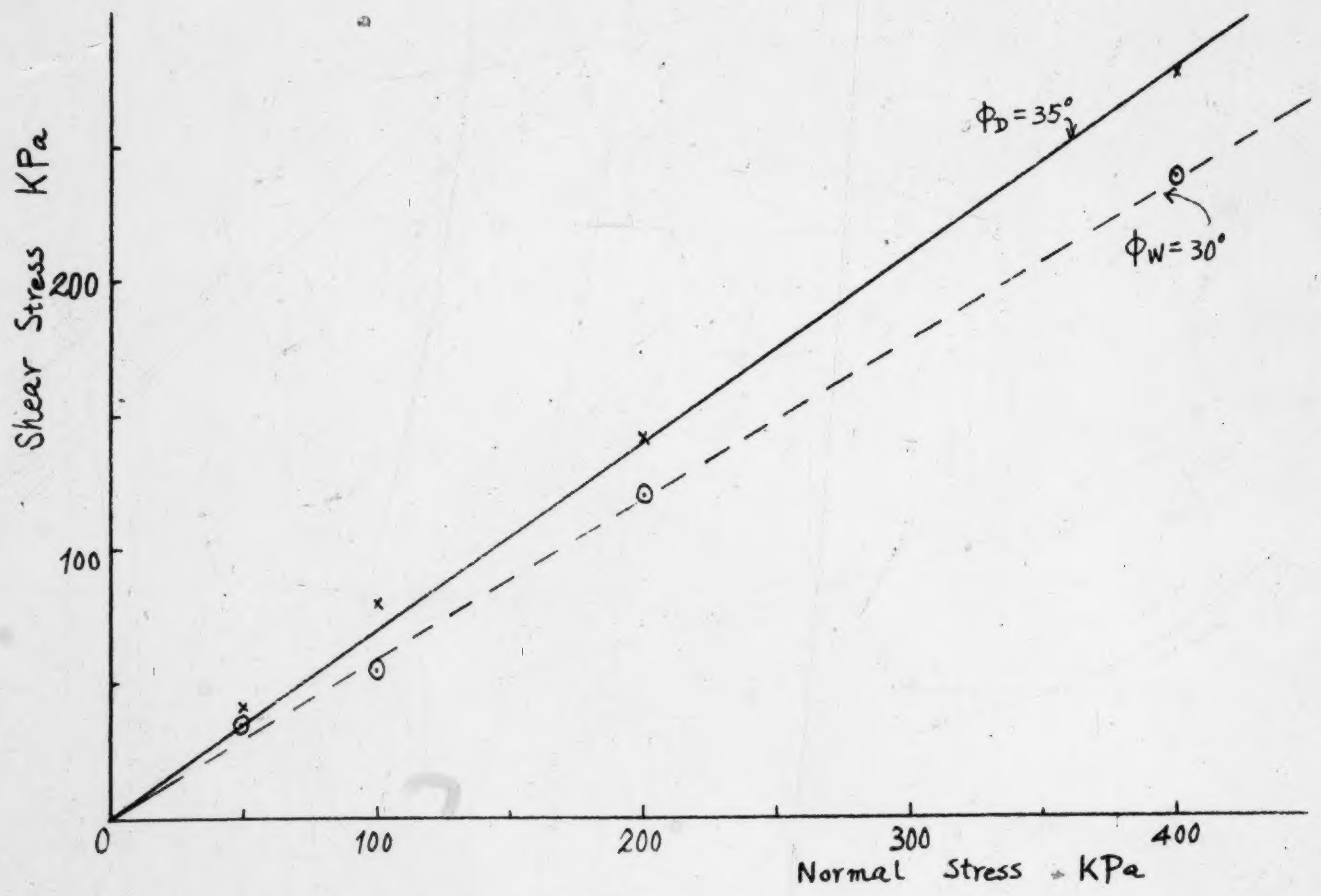

Figure 4.4 Shear Strength Envelope 1

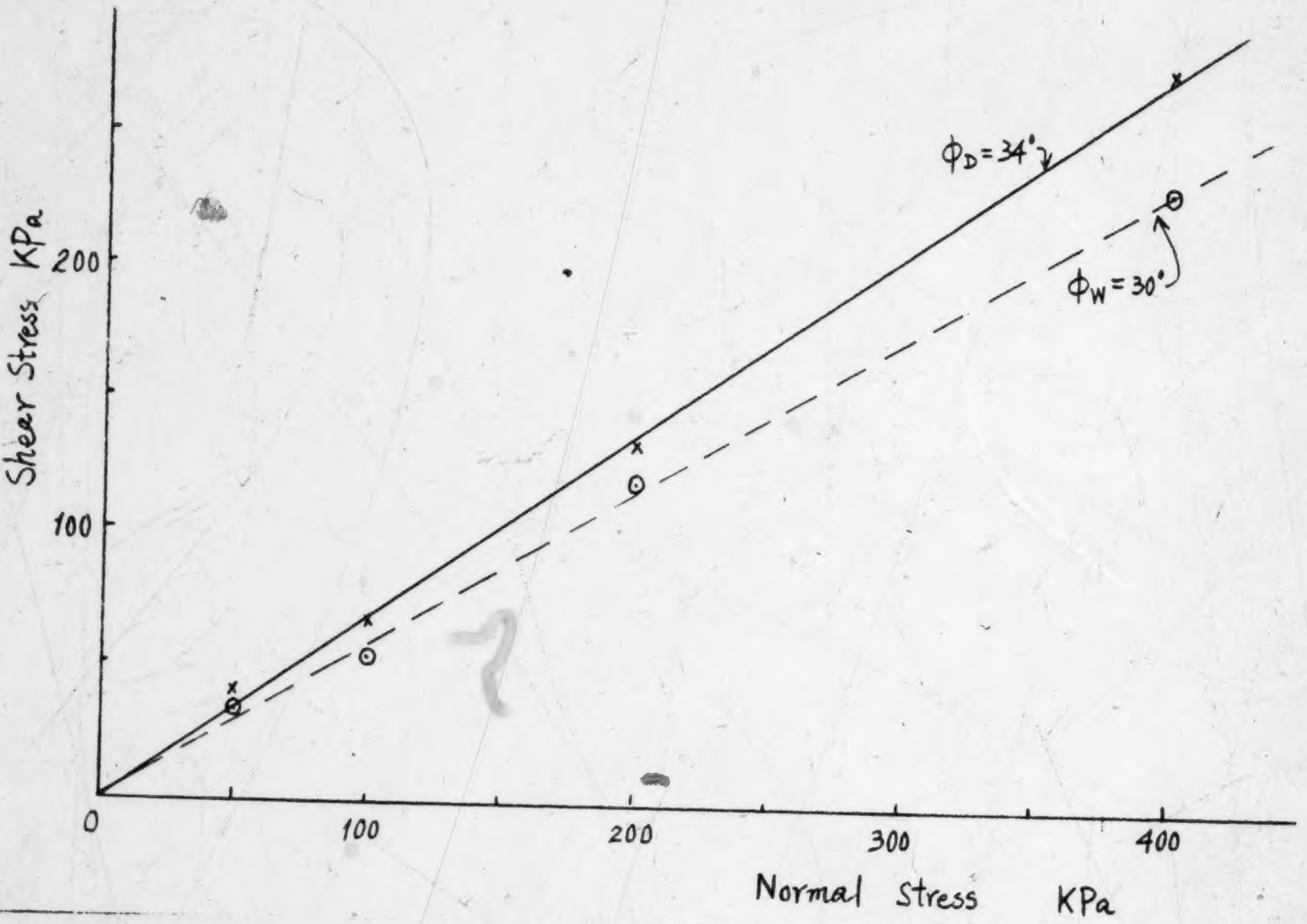

Figure 4.5 Shear Strength Envelope 2

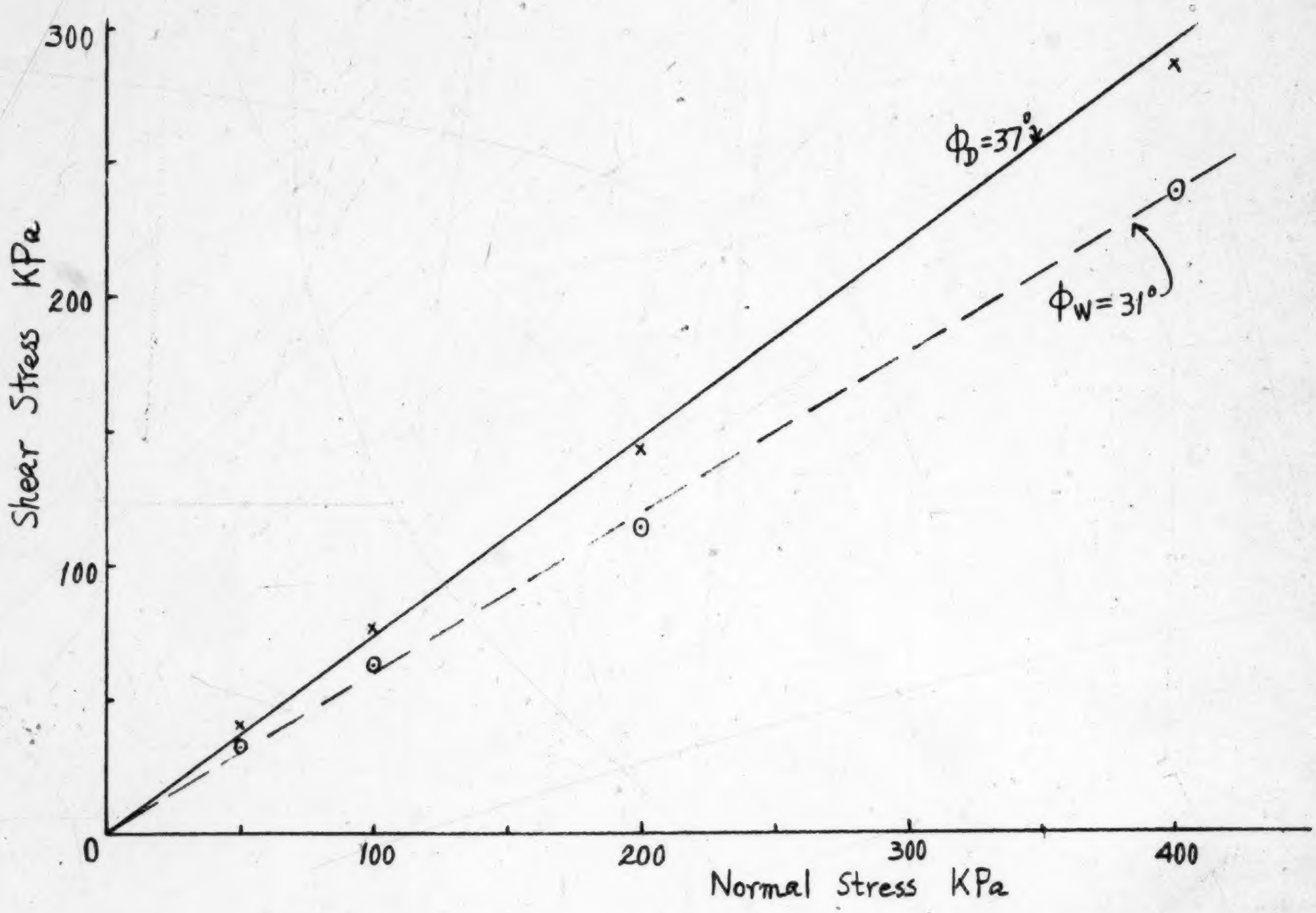

Figure 4.6 Shear Strength Envelope 3

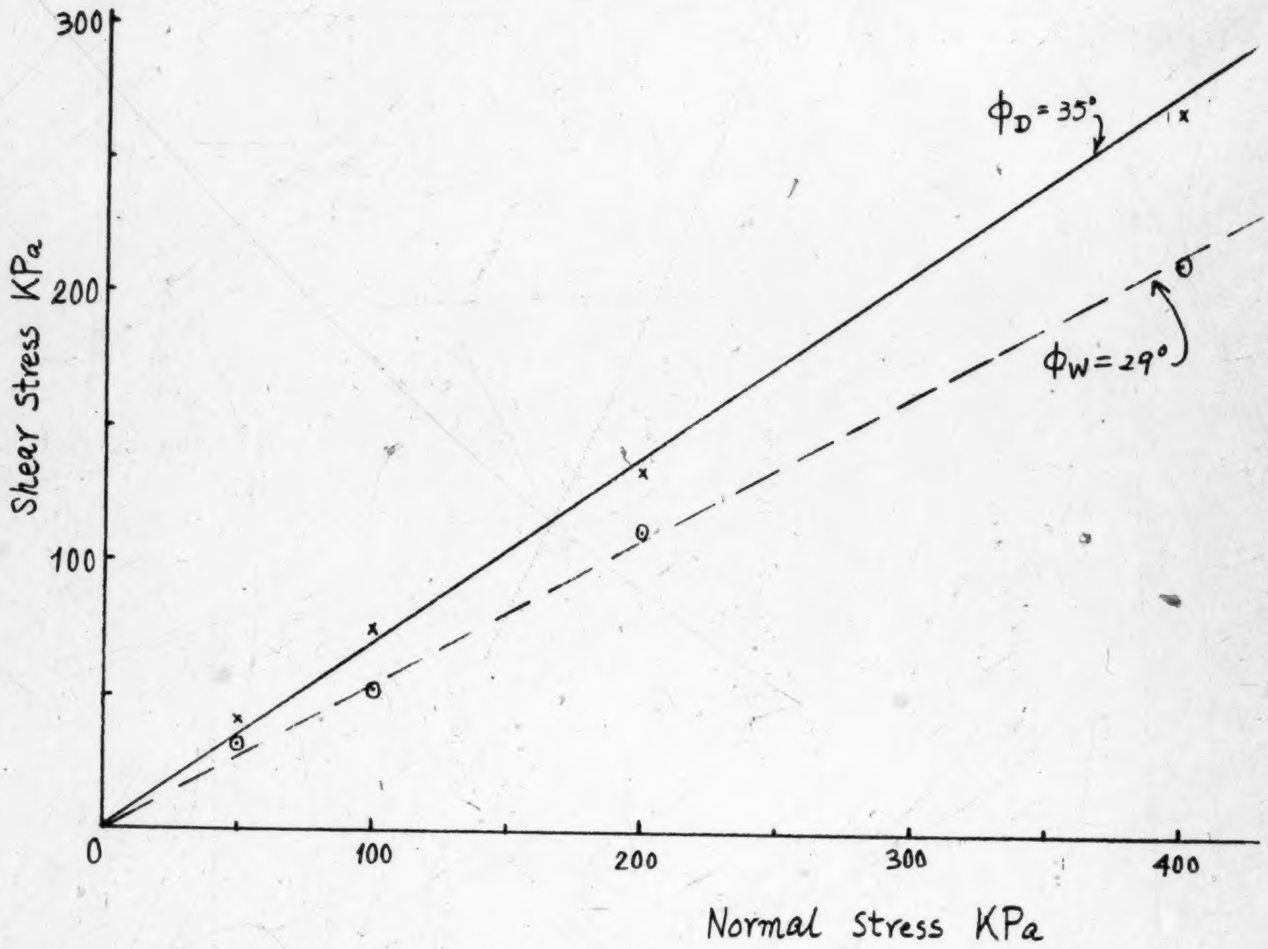

Figure 4.7 Shear Strength Envelope 4

It may be concluded that the shear strength of dry tuff ranges 34°-37°, with an average of 35°, and for wet tuff ranges 29°-31°, with an average of 30°.

4.7 Tilting Table Testing

The friction angle of dry tuff specimen was also measured by tilting table following Bruce et al. (1988). A pair of specimens with pre-cut surfaces were loaded on the tilting table. The friction angle was measured by a fixed protractor and LVDT respectively. The results are presented in Table 4.8. They are very well matched with the results from direct shear testing. The peak value of friction angle ranges 36°-39°.

4.8 Summary

The main results from the laboratory programme are:

1. The tuff has a low dry density (range of 1.28-1.47 g/cm^3, and average of 1.39 g/cm^3).

2. The tuff has a high porosity (range of 29.98%-43.11%, and average of 35.76%). The porosities indicate a material transitional between soil and the more common igneous, sedimentary and metamorphic rock types.

3. The tuff has very low Slake Durability Index (26%). It reflects the extensive presence of clay particles.

4. The tuff is characterised by low uniaxial compressive strength (q_u=5.4 MPa, when it is dry, and q_u=3.3 MPa, when it is wet.).

Table 4.8 Results of Tilting Table Testing

No	Øp	Øu
1-1	38°	31°
1-2	36°	31°
1-3	37°	31°
2-1	37°	32°
2-2	39°	32°
3-1	37°	32°
3-2	37°	31°
3-3	37°	29°

5. The tuff has high shear strength when dry (friction angle: 34°-37°). But the friction angle drops to 30° when it is saturated.

6. The volcanic tuff examined in this research is thought to constitute the basal rupture zone of the 1984 rock avalanche on Mount Cayley. The low uniaxial compressive strength, and low friction angle when it is wet seem responsible for the forming of rupture surface.

5. MECHANISMS OF ROCK AVALANCHES AND DEBRIS FLOWS ON MOUNT CAYLEY

5.1 Introduction

As discussed previously, the 1963 rock avalanche and the 1984 event on Mount Cayley show different characteristics. From the deposits of the 1963 rock avalanche, it is inferred that the event was a slide. Three rock blocks were detached from the scarp one after another. These blocks slid down the creek valley and came to rest at the confluece of Dusty and Turbid Creeks one after another. These three blocks keep their original stratigraphic order and structures. The 1984 event showed different processes and characteristics. The rock mass was detached from the scarp, slid down Avalanche Creek and came to rest around the confluece of Avalanche and Turbid Creeks. The deposits dammed these two creeks. As water accumulated behind it, the dam burst causing a large debris flow which travelled down Turbid Creek and eventually entered the Squamish River. Obviously, the 1984 event included two stages: a rock avalanche and a debris flow, but the 1963 event had only one single stage: a rock avalanche. The distances the rock debris travelled in these two events are different: the rock debris of the 1963 event slid 2.4 km downstream, and the debris of the 1984 event slid 1.6 km downstream first and then its deposits flowed 4.6 km.

Comparing the 1963 rock avalanche deposits with the 1984 rock avalanche deposits (the first stage deposits), it is found that the former shows distinct depositional units indicating that sliding process was dominant, and the latter shows massive characteristics (Figs. 3.5 and 3.6) indicating that avalanche process was dominant. Needless to say the second stage deposits of the 1984 event have totally different structures, thin, no depositional units, boulders deposited on the top and fine particles sticking on the surfaces of these boulders. Obviously, these two events have different mechanisms. The following sections will concentrate on the slope failure mechanism and the slope movement transformation mechanism.

5.2 Slope Failure Mechanism

From the deposits along the valley of Turbid Creek and the east bank of the Squamish River it is inferred that rock avalanches and debris flows have taken place on Mount Cayley after the deposition of the Quaternary volcanic rocks. Almost all rock avalanche deposits came from volcanic rocks. It is reasonable to assume that the characteristics and the structure of the volcanic rocks make them prone to slide.

The pre-existing joints, faults and the weak tuff layer and its geotechnical properties deeply influence slope stability on Mount Cayley.

5.2.1 Margins of Rock Avalanche

It is evident that the main scarps and lateral margins of these rock avalanches developed along a set of planar, nearly vertical joints. For example, the main scarp of the 1963 rock avalanche developed along a set of planar, nearly vertical southwest trending joints (Fig. 2.3). The gently curving, northwest lateral margin follows several north-northwest trending joints. Similarly, the main scarp of the 1984 rock avalanche developed along the planar, nearly vertical, southwest trending joints (Fig. 3.3). And the lateral margin follows a set of nearly vertical northwest trending joints. As shown in Figs. 5.1 and 3.3, these joints might be open before the rock avalanches took place. So snow melt and rainfalls can readily penetrate the slope and reach the potential rupture surface through these open cracks. Open cracks following those planar, nearly vertical joints have been observed on Mount Cayley, but these slopes have not failed yet. For example, these open cracks are seen on the slope next to the 1984 rock avalanche scarp downstreamwards, and the slope at the opposite side of the 1984 rock avalanche scarp. So open cracks may form some time before slope failure. It is reasonable to assume that the opening of these vertical faults and joints might be caused by the removing of the front part of the slope by creek down-cutting. So these nearly vertical cracks are not only the main cause of slope failure but also good indicators for prediction of slope failure. As shown in Fig.

Figure 5.1 Open Cracks Developed along Planar, Nearly Vertical Joints Locations as 3 and 4 shown on Fig. 1.2

5.2, these rock blocks isolated by those nearly vertical cracks are free to move.

5.2.2 Rupture Surface and Tuff Layer

It is evident that the tuff layers are the weakest zones in the volcanic piles compared to the columnar-jointed dacite and breccia. As shown in Fig. 5.3, ground water is seeping out along the top surface of the tuff layer indicating that the tuff layer has a low permeability comparing to other rock layers in the volcanic pile. In most cases, tuff layers form relatively inpervious units. So it is reasonable to assume that sufficient water may accumulate on the top of the tuff layer which would be fully saturated. Also, as shown in Fig. 5.3, the tuff layer dips towards the valley at 30°. Most tuff layers on Mount Cayley dip towards the valley at 15°-35°.

A shear zone parallel to the slope, dipping towards the valley developed in the columnar-jointed dacite is clearly shown in Fig. 5.4. Shear would be induced by the gravitational stresses in the slope, caused by the rapidly down-cutting. That kind of shear zone should also develop in tuff layers when they outcrop on the steep valley walls after rapid down-cutting. These shear zones would reduce the strength of tuff layers.

As indicated by the test results (in sections 4.3 and 4.4), the volcanic tuff has a low uniaxial compressive strength and very low slake durability. And the uniaxial

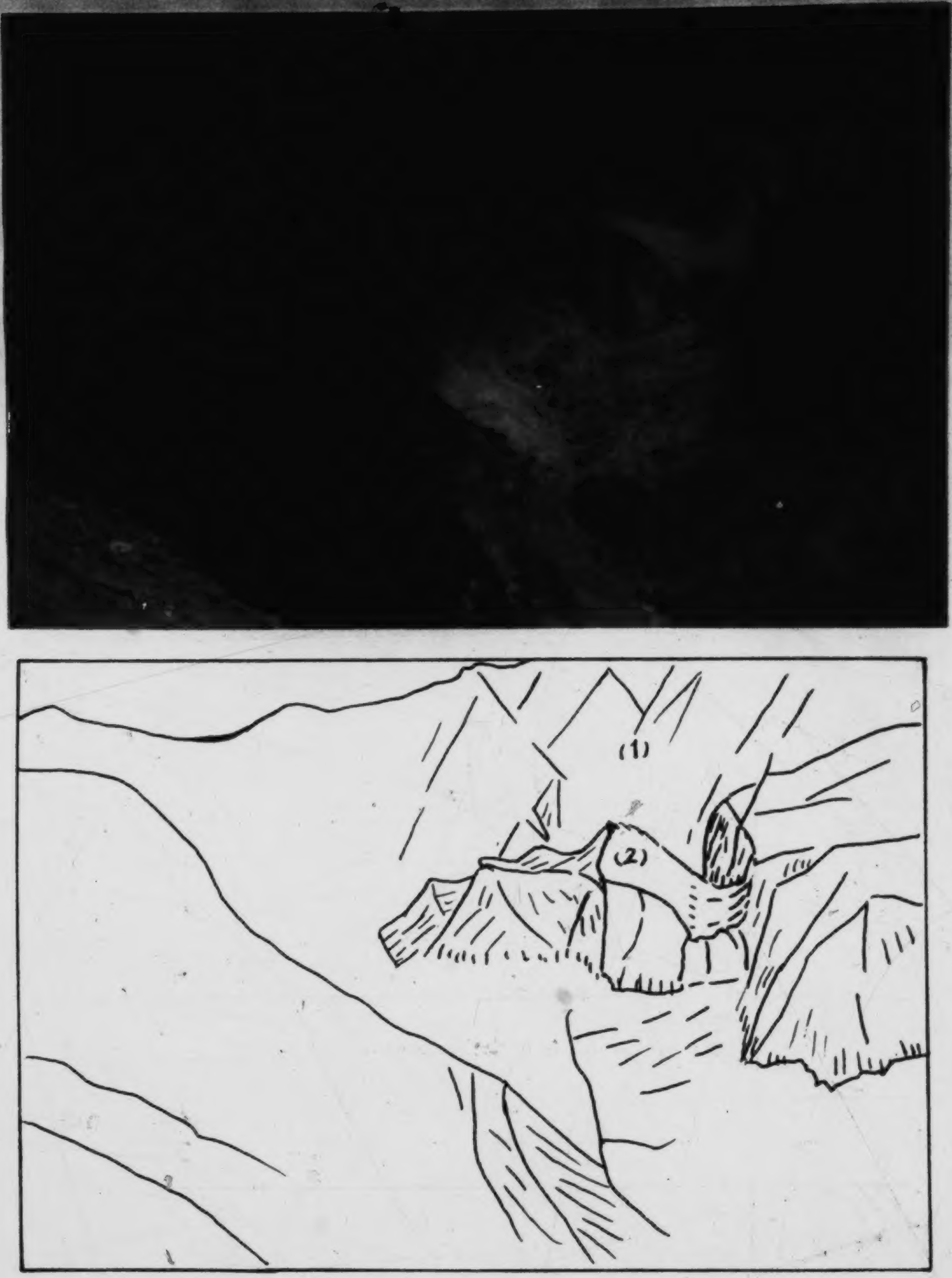

Figure 5.2 Isolated Blocks by Joints, Location Shown on Fig. 3.1

(1) Joints; (2) Isolated blocks.

Figure 5.3 Ground Water Seepage along Top of Tuff Layer

Figure 5.4 Shear Zones Parallel to Slope Dipping towards to Valley

compressive strength of wet tuff specimens is only about 65% of the dry ones (section 4.4). The direct shear test results (section 4.6) show that wet tuff specimens have a lower friction angle (30°) than the dry specimens (35°-37°). So full saturation may cause strength reduction. In addition, the top of the tuff layer may collapse and disintegrate into small particles resulting in further reduction of its strength (sections 4.3 and 4.4).

As a part of slope is isolated by those nearly vertical open cracks and the saturated tuff layer is a block freed from the slope, it may slide down along the weak tuff layer in the form of rock avalanche.

As mentioned in Chapters 2 and 3, the rupture surface of the 1963 rock avalanche developed mainly along a tuff layer, and the rupture surface of the 1984 rock avalanche developed along a weak tuff layer. These facts strongly support the analysis made above.

5.2.3 Slope Failure Mechanism

Rock avalanche events have been recognised on Mount Cayley, it seems that these slope failures may obey some similar mechanism. The special rock types-hard, columnar-jointed dacite and weak tuffs, the planar, nearly vertical joints are two essential causes leading slopes to fail. After the deposition of Quaternary volcanic rock, the creeks on Mount Cayley have cut through the volcanic rock already and developed new channels on basement rock. It indicates that neotectonic movement in this area is strong and it is another active cause leading slope to fail because it evokes rapid down-cutting. As a result, excessive stress difference develops at the toe of the slope, causing planar nearly vertical joints to become open. So isolated rock blocks formed (Thomson and Morgenstern 1977 and 1979).

Rainfall and snow melt water play an important role in slope failures on Mount Cayley also. The 1963 and the 1984 events took place in July and June 28 respectively, both in the summer. It is reasonable to assume that sufficient water accumulated on the top of tuff layer is a necessary condition for slope failure to take place on Mount Cayley.

As the failed slopes in 1963 and 1984 were 110 m and 150 m in height respectively, the self weights of these pre-slide slopes were approximately 3.3 MPa and 4.5 MPa respectively. The uniaxial compressive strength of dry tuff is 4.8-5.8 MPa. So the tuff layer would be able to sustain the slope when it is dry. Also as the dip angles of tuff layers vary from 15° to 35°, and the friction angle of dry tuff is about 35°, the slope could be stable when the tuff layer is dry. After water reached the top surface of tuff layer, the top of the tuff layer would gradually be saturated. Following the saturation process, the strength of tuff layer would be reduced, and finally drop to the point (3.2-4.0 MPa)which is below the self weight of these slopes. At that time, collapse would take place (section 4.4) and the friction angle would drop to the level of 30° or lower (section 4 6).This process would continue until the whole or, at least, most of the potential rupture surface was fully saturated and the strength of the total rupture surface was reduced. Then the block overlying it would slide down rapidly.

5.3 Transformation of Rock Avalanche into Debris Flow

The 1963 rock avalanche terminates at about 500 m (Chapter 2) the present confluence of Dusty and Turbid Creeks. Three blocks of deposits show distinct depositional units. So it is clear that the 1963 event contained one single stage, a rock slide or rock avalanche.

The 1984 event contained two separate processes, a rock avalanche and consequential debris flows. These two different slope movements are revealed by evidence such as the main scarp, slide dam remnant, typical rock avalanche deposits at the confluence of Avalanche and Turbid Creeks, and typical debris flow deposits in the middle and lower stream of Turbid Creek.

5.3.1 Evidence

As the debris flow stage can be easily determined by its deposits and a series of special phenomena, the main effort in this section will be concentrated on the first stage-rock avalanche to clearly exclude a possibility that the 1984 event might be a single process-debris flow, and no rock avalanche was involved.

The following evidence reveals the rock avalanche stage of the 1984 event.

5.3.1.1 Rock Avalanche Dam Remnant

As shown in Fig. 3.5, the dam remnant consists of large boulders of light yellow breccia and purple lapilli. There is no evidence showing that there was enough water involved in the movement and the deposition. No fine particles of purple tuff from the disintegration of purple lappili tuff when it encountered water can be seen in the remnant of the slide dam. This dam remnant observed in the summers of 1985 and 1986, and seen in the air photos taken in 1987, can not be seen in the air photos taken in 1982. So it is reasonable to assume that the natural dam was created by 1984 rock avalanche.

5.3.1.2 deposits

Thick deposits around the confluence of Avalanche and Turbid Creeks (Fig. 3.6) consist of boulders of light yellow breccia and purple lappili. It is evident that these deposits have totally different structure from debris flow deposits (see Figs. 3.12 and 3.13).

In Avalanche Creek above its confluence, no debris flow deposits have been found except the thick rock avalanche deposits.

5.3.1.3 Detached zone

Comparing the air photos taken in 1982 and 1987, a detached zone next to the head of Avalanche Creek can be easily determined (Fig. 5.5). But as shown in Fig. 3.1 the detached zone is clear. The photo was taken in the summer of 1985 from a helicopter by the author. Also the slide dam remnant, the massive deposits around the confluence, and the debris flow deposits in the middle and lower streams of Turbid Creek were observed in the 1985 and 1986 summers. The special rock, light yellow breccia and purple lapilli seen in the 1984 event deposits can be easily traced back to the detached zone.

So it is concluded that the detached zone seen in 1987 air photo is the very place where the 1984 event started. The evidence also indicated that the 1984 event began as a rock avalanche at the head of Avalanche Creek and terminated around the confluence of Avalanche and Turbid Creeks. At that time these two creeks were dammed by the rock avalanche debris.

5.3.1.4 Evidence of the Debris Flow

The evidence of debris flow is, as mentioned in Chapter 3, the 1984 event deposits in the middle and lower streams of Turbid Creek show typical characteristics such as a thin deposit layer covering a large area including different elevations and topographies, huge boulders deposited on the top of the thin layer and lots of fine particles sticking on their

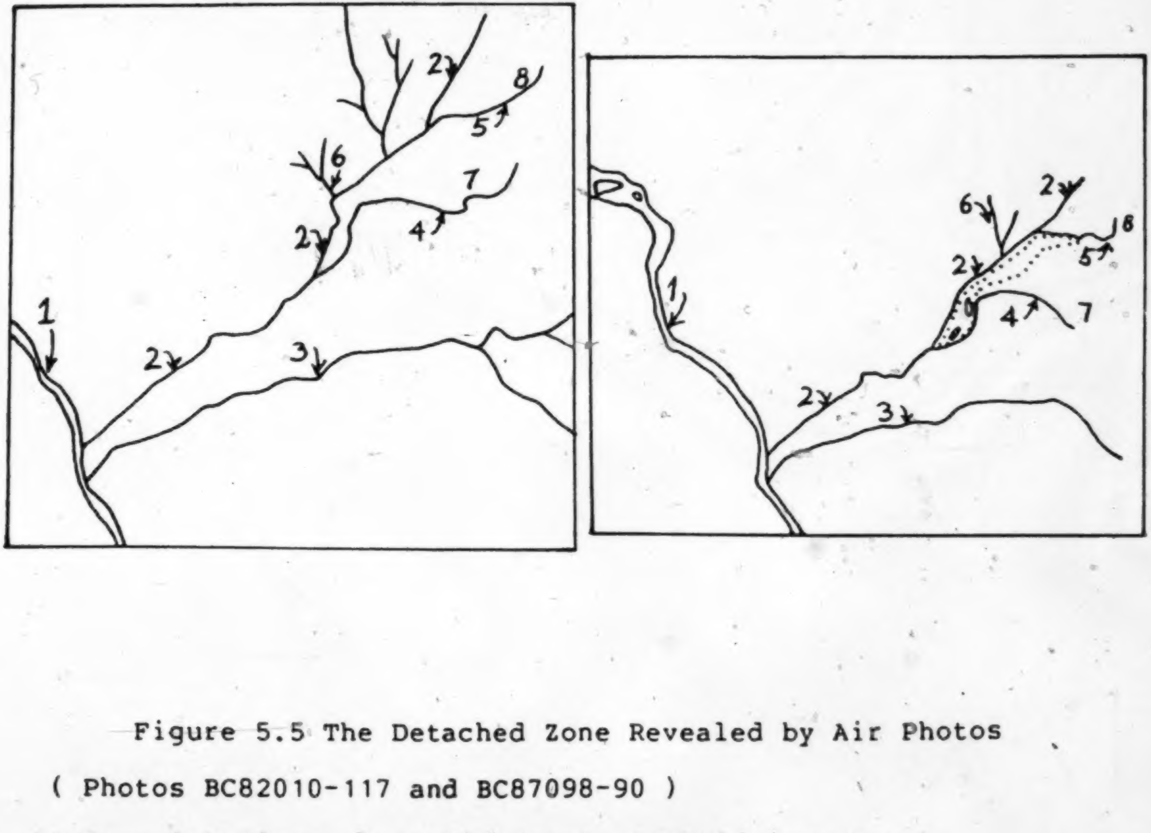

Figure 5.5 The Detached Zone Revealed by Air Photos (Photos BC82010-117 and BC87098-90)

1-Squamish River, 2-Turbid Creek, 3-Sholvenose Creek, 4-Dusty Creek, 5-Avalanche Creek, 6-No Name Creek, 7-Source Area of the 1963 Rock Avalanche, 8-Source Area of the 1984 Rock Avalanche, ▨ The Area Covered by 1984 Debris surfaces, and special rock belts (light yellow breccia) indicating that the rock debris was flooding on the top of the flow.

As also mentioned in Chapter 3, lots of mud was spattered from the moving debris and reached 16 m above the ground and stuck on the upstream sides of some large trees. These mud spatters imply that there were sufficent water involved in the second stage of the 1984 event.

Also, some people witnessed debris flow surges moving in the stream near the mouth of Turbid Creek. Fig. 3.26 recorded the passing debris flow.

5.3.2 Transformation of slope movement

It is inferred that the rock avalanche stage of the 1984 event terminated around the confluence of Avalanche and Turbid Creeks, and debris flows started from this area, because of the totally different deposits seen in this area and below.

The debris flow was caused by the outburst of the rock avalanche dam as water accumulated continuously behind the dam. Volcanic tuff blocks played a very important role in debris flow development. As indicated by slake durability testing (section 4.3), the volcanic tuff blocks are very easily broken and disintegrated into fine particles. The first cycle slake durability index (Table 4.6) indicates that more than 50% of the tuff blocks would disintegrate into fine particles after these dry tuff blocks encountered water and moved for 10 minutes. And about 75% of the tuff blocks would disintegrate into fine particles after two cycles of drying and wetting (Table 4.6). So after the outburst of the debris dam, lots of tuff blocks would disintegrate into fine particles in a short distance. Following that, these fine particles would participate in the flow and change it into slurry flow which would be able to carry huge boulders in suspension. Thus the debris flow was promoted by these fine particles.

As discussed by Pierson and Costa (P7, 1987)

" The flow of sediment-water mixtures having sufficient yield strength to exhibit plastic flow behavior in the field (that is, to form steep, lobate fronts and lateral levees, and to carry gravel-sized particles in suspension) and yet to become partially liquefied as they are remolded, is termed here slurry flow (after Carter, 1975)......Such a mixture will flow as a coherent, homogeneous mass when the yield strength is exceeded......Depending on the shear strength of the mixture and the dynamic particle-support mechanisms operating, particles to the size of large boulders can be suspended in slurry flow. Boulders exceeding the suspension competence of the slurry can be rolled along by the flow. When the flowing slurry comes to a stop, it consolidates at the rate at which the pore fluid can drain out with the exception of some of the clay and silt that escapes with the pore water, fine and coarse particles settle together without any interparticle movement. This is in contrast to hyperconcentrated flow, where particles settle out of suspension and are deposited separately, depending on their fall velocities (Qian and others, 1978). "

The phenomena and evidence observed in the field are almost exactly what Pierson and Costa expected. After the tuff blocks disintegrated into fine particles, a slurry flow formed first. The slurry flow carried large boulders suspended in the flow and travelled downstream rapidly. Consequently, typical debris flow deposits, fine and coarse particles settled together without any interparticle movement, formed when the debris flow came to rest.

5.4 Classification of Slope Movement

According to Varnes (1978), the 1963 event on Mount Cayley is classified as a rock slide, and the first stage of the 1984 event is also a rock slide. The second stage of the 1984 event, following Varnes too, is classified as debris flow.

From the rheologic point of view (Pierson and Costa, 1987), the second stage of the 1984 event is classified as inertial slurry flow. The main characteristic of inertial slurry flow is the interstitial fluid which is water and fines, clay particles from the disintegration of tuff. When the rheologic classification is fitted into existing flow nomenclature (Pierson and Costa P9 1987), the second stage of the 1984 event is also termed a debris flow, but almost reaches the highest velocity limit-30m/s.

Now, it is clear that the weak tuff layers are very important, not only responsible for slope failure, but also for the formation of an inertial slurry flow- a high velocity debris flow.

6. CONCLUSIONS

6.1 Conclusions

Field investigation shows that rock slides (avalanches) and debris flows have taken place quite on Mount Cayley since the deposition of Quaternary volcanic rocks. The remnants of head scarps, slide dams, and typical rock slide deposits and debris flow deposits are the records of these events. Among them, the 1963 rock avalanche and the 1984 rock avalanche and debris flow have been studied in detail.

The 1963 rock avalanche began at 1450 m and terminates at 500 m. About $5x10^6$ m^3 of columnar-jointed dacite and poorly consolidated pyroclastic rocks on a west-facing slope at the head of Dusty Creek detached from the head scarp, and slid downstream approximately 2.4 km along a slope of 21° from head to toe. It probably occurred in July, 1963. The average velocity of debris movement was about 16 m/s. The maximum thickness of moving debris was 70 m.

The whole accumulation zone of the 1963 rock avalanche is naturally divided into three blocks by their different depositional units and different topographic characteristics. Two evident gully-like depressions which can be seen on the air photos and in the field clearly separate these three deposit blocks.

The deposits of the 1963 rock avalanche have distinct depositional units which can be traced back to the source area. Each deposit block has its own depositional units which are different from the other blocks. These distinct depositional units are not only seen along the stream course of Turbid Creek, but also seen on the other side of the block along the present stream course of Dusty Creek, both sides of the block show the same depositional units and structure. So it is inferred that the 1963 rock avalanche contained three separated rock blocks in the source area, which detached from the head scarp one after another and came to rest at different localities and times, also one after another.

As a result, Dusty and Turbid Creeks were seriously blocked by the 1963 rock avalanche deposits. Turbid Creek was diverted by the thick debris deposits shifting about 200 m westwards, the confluence of Dusty and Turbid Creeks shifted 1 km downstream. Accompanying the deposition of rock debris, Dusty Creek took over a part of pre-slide stream course of Turbid Creek, then joins Turbid Creek at the present confluence again.

As the deposits of the 1963 event show distinct stratigraphic units, it is inferred that the 1963 event was a slide differing from the 1984 event.

The 1984 event occurred on June 28. The slope failure started at 1500 m, next to the head of Avalanche Creek. Approximately $6x10^{6}$ m^{3} of volcanic rock, mainly the top unit, light yellow breccia and purple lapilli, detached from the scarp and slid downstream.

The 1984 event includes two stages, rock avalanche and debris flow.

In the first stage, a rock mass approximately 200x300x150 m detached from the slope , slid south, dug into the valley bottom and picked up lots of ice blocks, impacted the south-east wall of the valley and broke up. Then the rock debris travelled downstream, largely confined to the valley of the creek. Finally the rock debris overtopped the small ridge between Avalanche and Turbid Creeks, left a significant superelevation mark on the west (right) bank of Turbid Creek, and came to rest around the confluence and dammed these two creeks. In the remnant of the rock avalanche dam and the deposits on the east (left) bank of Turbid Creek, no distinct depositional units like the 1963 deposits are seen.

In the second stage, the water coming from the upstream of Turbid Creek and the melted ice blocks accumulated continuously behind the dam. The increasing water pressure finally caused the dam to burst. Debris flow surges formed, moving with a high velocity. In the middle stream of Turbid Creek, the debris flow shifted its moving direction quite often, even overtopped the top of the escarpment consisting of the 1963 rock avalanche deposits on the south-east (left) side of the valley of Turbid Creek, rushed into Dusty Creek and left some deposits on the both sides of Dusty Creek. As a result, almost the whole valley in the middle stream of Turbid Creek was covered by a thin (generally

0.5-2.0 m) debris layer consisting of special rocks-light yellow breccia and purple lapilli.

Local velocities of the rock avalanche were determined from the superelevations to be 32 m/s. The velocity of the debris flow was 28-32 m/s.

As the debris flow moved at such a high velocity, a series of special phenomena were created. The most significant ones are high superelevation, uprooted trees, high mud spatters, and wood pieces and rock blocks hurled through air.

Even though the velocity of the debris flow was significantly reduced, the debris flow still removed the logging road bridge and road approches completely, almost blocked the Squamish River during each surge, swept 3 km of logging road and introduced huge quantities of sediments to the channel of the Squamish River, leading to significant channel change in this part of the river. The major debris flow lasted for at least 2 hours.

The slope failure mechanism on Mount Cayley may be as follows

Planar, nearly vertical south-west and north-west trending fault zones and joints are one of essential factors causing slope failure on Mount Cayley. After significant down-cutting accompanied the strong neotectonic movement in this area, these faults and joints become open and cracks, which not only cut the slope into blocks but also facilitated rainfall and snow melt to penetrating the slope.

As tuff layers dip towards the valley at 15°-35°, and shear planes parallel to the slope and dipping towards the valley may have developed in these tuff layers, so potential failure surfaces may easily develop along one of tuff layers. These discontinuties separated the rock mass from the slope as isolated block or blocks. These blocks are free to move.

The tuff layers are not only the weak zones in the volcanic pile but also the impervious units. So ground water would accumulate around the top surfaces of tuff layers. As testing shows that the uniaxial compressive strength of wet tuff specimens is just 3.2-4.0 MPa, about 2/3 of the strength of dry specimens, and the friction angle of wet tuff specimens is 30° (35°-37° for dry specimens). Rock blocks having a height of 100-150 m, separated from the slope may fail when the tuff layer, the potential slip surface, is fully saturated. This may be the reason why both the 1963 and the 1984 events occurred in summer time, because significant snow-melt penetrated the slope mainly through the nearly vertical open cracks and accumulated on the top of tuff layer at that time, so the strength of tuff layer dropped to the point below the gravitational stress. Then the block or blocks slid down rapidly.

The mechanism of transformation of rock avalanche into debris flow may be as follows.

After damming of Turbid Creek, water from the upstream of the creek and snow-melt accumulated behind the debris dam. When the water pressure exceeded the strength of the debris, the dam burst and debris flow surges formed.

As indicated by slake durability tests, the volcanic tuff blocks easily disintegrate into fine particles when they encounter water. When these fine particles, mostly clay minerals, mixed with water, the flow tended to a slurry flow. Depending on the dynamic particle-support mechanisms, particles to the size of large boulders can be suspended in the slurry flow. Thus, viscous debris flow surges formed and travelled at a high velocity. These viscous debris flow surges created high mud spatters and special deposits, fine and coarse particles settled down together without any interparticle movement as observed in the middle and lower streams of Turbid Creek.

6.2 Recommendation for Further Research

1. Numerical model research

In this first step of study, no attempt has been made to set up numerical models for the rock avalanches on Mount Cayley. It should be the main part of further research. For this purpose, precise profiles of the source areas of these rock avalanches should be made, and some more precise testing, such as triaxial compressive testing should be carried out. Also the structure and the composition of volcanic tuff should be examined in detail.

2. Rock avalanche prediction

As logging and recreation bring more people into this area, the catastrophes which may be caused by rock avalanches and debris flows in the area should be carefully estimated and predicted. In addition, attention should be paid to the Squamish River. If a large rock avalanche took place on Mount Cayley while the river was fully filled with water, debris flows or floods may occur in the Squamish River. They may cause serious damage to the communities along the river, even the town of Squamish. To prevent these catastrophes, rock avalanche prediction based on the monitoring of some open cracks should be considered in advance.

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